Global warming of 1.5 °C

An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

TEXT

Chapter 1: Framing and Context

Executive Summary

1.1 Human, ecological, and physical dimensions of 1.5 °C: Building a knowledge base for this report

1.2 Understanding 1.5 °C; reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5 °C and 2 °C for use in this report

1.2.1.1 Choice of variable:

1.2.1.2 Choice of reference period:

1.2.1.3 Total, expected or human-induced warming:

1.2.1.4 Summary:

1.2.2 Global versus regional and seasonal warming

1.2.3 Definition of 1.5 °C consistent pathways and associated emissions

1.2.3.1 Temperature stabilization pathways

1.2.3.2 Temperature overshoot pathways

1.2.3.3 Continued warming pathways

1.2.3.4 Precautionary versus adaptive mitigation scenarios

1.2.3.5 Cumulative emission budgets

1.2.4 Definition of "balance" and net zero emissions

Box 1.1: Long-lived and short-lived climate pollutants and emission metrics

1.2.5 Definitions of warming commitment

1.3 Multiple dimensions of impacts at 1.5 °C and beyond

1.3.1 Detection and attribution of impacts

1.3.2 Physical Dimensions of Impacts

1.3.2.1 Spatial and temporal distribution of impacts

1.3.2.2 Implications of 1.5 °C for extreme events and associated impacts

1.3.2.3 Non-temperature related impacts

1.3.2.4 Probability and uncertainty of impacts

1.3.2.5 Deterministic (e.g. sea level rise) versus stochastic (e.g. extreme weather) impacts

1.3.2.6 Permanence and irreversibility

1.3.3 Human Dimensions of Impacts, including adaptive capacity

1.3.3.1 Sectoral impacts

1.3.3.2 Spatial and temporal dimensions

1.3.3.3 Human settlements

1.3.3.4 Poverty, equity and justice

1.3.4 Ecosystem Impacts

1.4 1.5 °C in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, with consideration for ethics and equity

1.4.1 The different dimensions of "feasibility"

1.4.2 The adaptation-mitigation-sustainable development nexus: tradeoffs, synergies and co-benefits

1.4.3 Implementation and governance

1.4.4 Timescales and transformation

1.4.5 Enabling an adaptive response to emerging trends and extreme events

1.4.6 Justice, equity and ethics

1.4.7 Multidimensional costs and benefits

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

1.5.1 Building on AR5 and SREX

1.5.2 Types of knowledge and evidence used in the report

Box 1.2: Experiencing 1.5 °C - Opportunities and challenges of visualizing a 1.5 °C world using observations of climate impacts today; climate change and variability to date; extreme weather and the potential role of community knowledge

1.5.3 Assessment across space and timescales (Assessment and methodologies across space and timescales)

1.5.4 System-level framing: Anthropocene, transition theory, transformative change

1.5.5 Transformation, Transformation Pathways, and Transition

1.5.6 Building social, institutional and knowledge capital

1.6 Consideration and communication of confidence, uncertainty and risk

1.6.1 Background – confidence scale:

1.6.2 Background – likelihood scale:

1.6.3 Challenges in the context of this Special Report:

1.7 Storyline of the report

References

Chapter 2: Mitigation pathways compatible with 1.5 °C in the context of sustainable development

Executive Summary

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

2.1.1 Mitigation Pathways compatible with 1.5 °C

2.1.2 Contextualizing 1.5 °C pathways

2.1.3 Sustainable development context of 1.5 °C and other mitigation pathways

2.1.4 New information and improved understanding since AR5

2.2 Assessment methods

2.2.1 Relationship to AR5 and new scenario literature

Table 2.1: New IAM studies that this chapter will draw upon and the key questions that can be explored by the scenarios of each study.

2.2.2 Description of assessment tools and methods

2.2.2.1 Literature assessment

2.2.2.2 SSP framework

2.2.2.3 Integrated assessment models

2.2.2.4 Geophysical assessment tools

2.2.2.5 Other tools (if necessary)

Table 2.2: List of assessment tools, model characteristics of particular importance for 1.5 °C pathways, and a short discussion of them being fit for purpose. [All values are illustrative at the moment and not based on any assessment whatsoever.]

2.2.3 The scenario approach

2.2.3.1 Pathway modelling as a discourse tool

2.2.3.2 What´s a scenario and how does it relate to “pathway”

2.2.3.3 Types of scenarios

2.2.3.4 Scenario assumptions

2.2.3.5 Short explainer of what it means if a scenarios was feasible

2.2.3.6 Database, including reference (baseline)

2.2.4 Concept of consistent and required characteristics

2.2.5 Risk management framing

2.2.5.1 Risk of failure to achieve pathway

2.2.5.2 Risk of failure to achieve desired outcome even if pathway is achieved

2.2.5.3 Adaptive management

2.3 Geophysical relationships and constraints

2.3.1 Introduction

2.3.2 Carbon budgets and contribution of non-CO_2 greenhouse gases and aerosols

Table 2.3: Carbon budget overview inspired by AR5 SYR Table 2.2

2.3.2.1 Improvements in understanding of geophysical processes since AR5

2.3.2.2 Geophysical basis for low emission pathway carbon budgets

2.3.2.3 Role of non-CO_2 gases and aerosols

2.3.2.4 1.5 °C and 2 °C carbon budgets and their uncertainty

2.3.3 Introduction to carbon and emissions neutrality, metrics

2.3.4 Geophysical response to carbon dioxide removal: carbon cycle and temperature

2.3.4.1 Effect on CDR to remove CO_2 from the atmosphere

Table 2.4: Overview CDR characteristics, as in AR5 WG3, Table 6.15.

2.3.4.2 Side-effect and geophysical limitation of CDR

2.3.5 Assessment of simple model performance in context of most recent literature

2.3.5.1 Tuning and calibration

2.3.5.2 Assessment in terms of carbon budget and temperatures outcomes

2.3.6 Pathway categorization in terms of temperature outcomes (peak and other)

2.3.6.1 Mid-term and transient likelihood of exceeding 1.5 °C or 2 °C

2.3.6.2 Long-term and equilibrium likelihood of achieving 1.5 °C or 2 °C

2.3.7 Overshoot, reversibility, feedback, temperature characteristics & extensions beyond 2100

2.3.7.1 Overshoot in temperature and CO_2

2.3.7.2 Tipping-point and feedbacks

2.3.8 How SRM affects carbon budgets, pathways and overshoots.

2.4 General characteristics of stringent global mitigation pathways

2.5 Transition characteristics of 1.5 °C pathways in the near-to-medium term

2.6 Properties of 1.5 °C pathways after mid-century

Table 2.5: Characteristics of socio-economic systems consistent with low temperature goals, including 1.5 °C

Table 2.6: Source: IPCC Special Report (2005)

Table 2.7: Maybe also a table is useful here. Example Climate Action Tracker (2015)

2.7 Co-impacts, opportunities, and challenges

2.7.1 Introduction

2.7.2 Policy and international governance

2.7.3 Technology and behavioural interplay

2.7.4 Economics and financial issues

Table 2.8: concept

2.7.5 Sustainable development and mitigation pathways

2.8 Knowledge gaps

2.9 Cross-cutting boxes [potential ideas]

2.10 Case studies [potential ideas]

References

Chapter 3: Impacts of 1.5 ºC global warming on natural and human systems

Executive summary

3.1 Background and framing

3.1.1 Scope and road map: structure of chapter

3.1.2 Conclusions from previous assessments (SREX, AR5)

3.1.3 Refer to definitions of key terms

3.1.4 Overview, storyline and relationship to other chapters

3.1.5 End point chapter

3.2 Methods of assessment

3.2.1 Introduction

3.2.2 Methods for assessing observed and projected climate and weather changes at 1.5 °C

3.2.2.1 Overview

3.2.2.2 Definition of a "1.5 °C or 2 °C climate projection"

3.2.2.3 Climate models and associated simulations and datasets available for the present assessment

3.2.2.4 Methods for the attribution of observed changes in climate and their relevance for assessing projected changes at 1.5 °C or 2 °C global warming

3.2.3 Methods for assessing observed impacts and projected risks to natural and managed systems and human settlements at 1.5 °C

3.2.3.1 Overview

3.2.3.2 Definition of a "1.5 °C or 2 °C impact projection"

3.2.3.3 Modelling approaches

3.2.3.4 Detection & attribution methods

3.2.3.5 Synthesizing aggregated impacts

3.2.4 Assessing avoided impacts at 1.5 °C vs. 2 °C and higher levels of warming

3.2.4.1 Identifying hot spots

3.3 Global and regional climate changes and associated hazards: Observed changes (including paleo); attributed changes; projected risks; avoided risks at 1.5 °C

3.3.1 Global changes in climate

3.3.1.1 Introduction

3.3.1.2 Global changes in temperature and precipitation

3.3.1.2.1 Observed and attributed changes

3.3.1.2.2 Projected changes at 1.5 °C

3.3.1.3 Summary on global changes in key climate variables and climate extremes

Table 3.1: Summary on global changes in key climate variables and climate extremes: Detected observed changes, attributed observed changes, and projected changes at 1.5 °C and 2 °C global warming, including both transient changes and changes at equilibrium. Assessments

are provided qualitatively (top half of cell) and if available also quantitatively (bottom half of cell). Symbols for references are: S12 (Seneviratne et al. 2012), H13 (Hartmann et al. 2013), B13 (Bindoff et al. 2013), and C13 (Collins et al. 2013).

3.3.2 Temperature on land, including extremes

3.3.2.1 Observed and attributed changes

3.3.2.2 Projected changes in temperature at 1.5 °C vs. 2 °C

3.3.3 Precipitation, including heavy precipitation and monsoons

3.3.3.1 Observed and attributed changes

3.3.3.2 Projected changes in precipitation at 1.5 °C vs. 2 °C

3.3.4 Drought and dryness

3.3.4.1 Observed and attributed changes

3.3.4.2 Projected changes in drought and dryness at 1.5 °C vs. 2 °C

3.3.5 Wind

3.3.6 Storms and tropical cyclones

3.3.7 Runoff and flooding

3.3.8 Snow and permafrost

3.3.9 Ocean chemistry

3.3.10 Ocean circulation and temperature (e.g., upwelling)

3.3.11 Sea ice

3.3.12 Sea level

3.3.13 Identified hot spots based on regional climate changes and associated hazards.

3.4 Observed impacts and projected risks in natural and managed ecosystems

3.4.1 Introduction

3.4.2 Terrestrial and wetland ecosystems

3.4.2.1 Observed impacts

3.4.2.1.1 Palaeoecological evidence

3.4.2.1.2 Global overview of impacts on major ecosystem components and functions

3.4.2.1.3 Observed impacts on major regions and ecosystem types

3.4.2.2 Projected risks and potential adaptation (including limits)

3.4.2.2.1 Global overview of projected risks to major ecosystem components and functions

3.4.2.2.2 Projected risks to major regions and ecosystem types

3.4.3 Coastal and low lying areas (inc. small islands)

3.4.3.1 Observed impacts

3.4.3.2 Projected impacts

3.4.4 Ocean systems including coral reefs

3.4.4.1 Observed impacts

3.4.4.1.1 Background

3.4.4.1.2 Impacts arising from rising ocean temperatures

3.4.4.1.3 Impacts from changing ocean chemistry

3.4.4.1.4 Other climate change drivers

3.4.4.1.5 Impacts on fisheries

3.4.4.2 Projected risks and adaptation options

3.4.5 Freshwater Resources (quantity and quality)

3.4.5.1 Observed impacts

3.4.5.1.1 Stream flow

3.4.5.1.2 Groundwater

3.4.5.1.3 Water quality

3.4.5.1.4 Soil erosion and sediment load

3.4.5.1.5 Extreme hydrological events (floods and droughts)

3.4.5.2 Projected risks and potential adaptation (including limits)

3.4.5.2.1 Stream flow including availability of water resources and water use

3.4.5.2.2 Water use:

3.4.5.2.3 Groundwater:

3.4.5.2.4 Water quality:

3.4.5.2.5 Soil erosion and sediment load

3.4.5.2.6 Extreme hydrological events (floods and droughts)

3.4.6 Food security and food production systems (including fisheries)

3.4.6.1 Observed impacts

3.4.6.1.1 Crop production

3.4.6.1.2 Livestock production

3.4.6.1.3 Fisheries Production

3.4.6.1.4 Food security

3.4.6.2 Projected risks and potential adaptation (including limits)

3.4.6.2.1 Crop Production

3.4.6.2.2 Livestock Production

3.4.6.2.3 Fisheries Production

3.4.6.2.4 Food security

Box 3.1: Mediterranean Basin and the Middle East droughts

3.5 Observed impacts and projected risks in human systems

3.5.1 Introduction

3.5.2 Urban areas --transport, energy, water, housing (including slums/informal settlements)

3.5.2.1 Observed impacts

3.5.2.2 Projected risks at 1.5 °C and 2 ºC

Box 3.2: Urban Climate

3.5.3 Rural areas

3.5.3.1 Observed impacts

3.5.3.2 Projected risks at 1.5 °C and 2 ºC

3.5.4 Key economic sectors and services

3.5.4.1 Introduction of context and expectations

3.5.4.2 Identifying key sectors for possible coverage

Box 3.3: Key economic sectors and services - An illustrative box example for coastal communities

Box 3.4: Key economic sectors and services - An illustrative box example for agriculture

3.5.4.3 Concluding remarks

3.5.5 Human health

3.5.5.1 Observed impacts

3.5.5.2 Detected impacts since AR5

3.5.5.3 Projected risks at 1.5 ºC and 2 ºC

Table 3.2: Projected risks to human health: studies cited in Smith et al. (2014)

3.5.6 Human security

3.5.6.1 Observed impacts

3.5.6.2 Projected risks at 1.5 °C and 2 ºC

3.5.7 Livelihood and poverty

3.5.7.1 Observed impacts

3.5.7.2 Projected risks at 1.5 °C and 2 ºC

3.5.8 Observed adaptation effectiveness and barriers

3.5.8.1 Investments in adaptation

3.5.8.2 Effectiveness of adaptation investments

3.5.8.3 Evidence of barriers and limits to adaptation

3.5.8.4 Maladaptation

3.6 Avoided impacts and reduced risks at 1.5 °C compared with 2 °C

3.6.1 Introduction

3.6.2 Synthesis on previous sections (3.3-3.5)

3.6.2.1 The physical climate system

3.6.2.1.1 Changes in climatological averages (Section 3.3 text to serve as input)

3.6.2.1.2 Changes in extreme weather events (Section 3.3 text to serve as input)

3.6.2.1.3 Large scale singular events (Section 3.3 text to serve as input)

3.6.2.2 Natural and managed ecosystems

3.6.2.3 Human systems

3.6.2.4 Global aggregate impacts (will be composed using section 3.3 to 3.5 as key inputs)

3.6.3 Benefits analysis Economic benefit analysis for a 1.5 °C vs. 2 °C global temperature goals

3.6.3.1 Reduced climate costs under 1.5 °C vs. 2 °C of global warming.

3.6.3.2 Potential trade-offs: mitigation costs associated with achieving 1.5 °C vs. 2 °C of global warming.

3.6.4 Compare 1.5 °C vs. 2 °C and NDCs/other baselines; consider impacts of alternative interpretations of 1.5 scenarios

3.6.4.1 Benefits of achieving the 1.5 °C and 2 °C of global warming as opposed to lower mitigation futures.

3.6.4.1.1 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with the Paris Agreement NDCs

3.6.4.1.2 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with low mitigation: 3 °C and 4 °C of global warming

3.6.4.1.3 Interpretation of different definitions of the 1.5 °C temperature increase to benefits analysis

3.6.5 Reducing hot spots of change for 1.5 ºC and 2 ºC global warming

3.6.5.1 The physical climate system

3.6.5.2 Natural and managed ecosystems

3.6.5.3 Socio-economic human systems

3.6.6 Tipping points

3.6.6.1 Tipping points in the physical climate system

3.6.6.2 Tipping points in ecosystems

3.6.6.3 Tipping points in human socio-economic systems

Table 3.3: Summary of enhanced risks in the exceedance of tipping points for 3 °C and 2 °C vs 1.5 °C of global warming.

3.7 Implications for impacts, adaptation and vulnerability of different mitigation pathways reaching 1.5 °C including potential overshoot

3.7.1 Pathways without overshoot

3.7.1.1 Likely pattern of extremes and other changes in climate system

3.7.1.2 Implications for natural and human systems

3.7.1.3 Adaptation options

3.7.2 Pathways with overshoot

3.7.2.1 Likely pattern of extremes and other changes in climate system

3.7.2.2 Implications for natural and human systems

3.7.2.3 Adaptation options

3.7.3 Non-greenhouse gas implications and projected risks of mitigation scenarios

3.7.3.1 Influence on weather and climate extremes

3.7.3.2 Impacts on natural and human systems (e.g. competition for land/water and food/energy security)

3.7.4 Long-term implications

References

Chapter 4: Strengthening and implementing the global response

Executive Summary

4.1 Introduction

4.1.1 The Anthropocene & AR5 as a starting point

4.1.2 Framing systems: ecological, social, economic, innovation

4.1.3 Global context and dynamics

4.1.4 Global response: Paris Agreement

4.1.5 Reading guide and place in this Special Report

4.2 Visions of 1.5 °C worlds

4.2.1 Temporal and spatial envelopes and dynamics of 1.5 C worlds

4.2.1.1 A selection of the SSPs

4.2.1.2 Other modelling frameworks and visions

4.2.1.2.1 Visions of a different socio-technical system

4.2.1.2.2 Visions of sustainable development and adaptation

4.2.1.2.3 Visions of sustainable lifestyles

4.2.1.2.4 Visions of 1.5°C worlds with Solar Radiation Management

4.2.1.2.5 Visions of 1.5°C worlds with Carbon Dioxide Removal

Box 4.1: CDR and urban geoengineering

Box 4.2: Complex systems and wicked problems

4.2.1.3 Uncertainties

4.2.2 State of sustainable development and transformations

4.2.2.1 Environmental systems

4.2.2.2 Economic systems

4.2.2.3 Social systems

4.2.2.4 Integrated systems for 1.5 °C worlds

4.3 Getting to 1.5 °C worlds: transitions and transformative pathways

4.3.1 Comparison of relevant pathways to 1.5 °C worlds with historical trends and social acceptance

4.3.2 Mitigation

4.3.2.1 Unpacking the 1.5 °C pathways: how to reach 1.5 °C worlds

4.3.2.2 Discontinuous pathways: additional levers for 1.5 °C

4.3.2.2.1 Innovation – beyond learning curves and technology diffusion assumptions in scenarios

4.3.2.2.2 Demand side (especially difficult-to-decarbonize sectors like transport) – lifestyle changes etc.

4.3.2.2.3 Non-CO_2 GHGs

4.3.2.2.4 Economic systems

4.3.3 Adaptation (based on input from chapter 3 on risks, exposure, vulnerability)

4.3.3.1 What does 1.5 °C mean for adaptation?

4.3.3.2 How far do adaptation commitments get us in managing the impacts of 1.5 °C?

4.3.3.3 Pathways to 1.5 °C adaptation

4.3.3.3.1 Sustainable development and adaptation to 1.5 °C

4.3.3.3.2 Transformational adaptation and 1.5 °C

4.3.3.3.3 Top-down and bottom-up approaches and cross-scale integration

4.3.3.4 Costs, benefits, trade-offs and risks of adaptation

4.3.3.4.1 Costs and benefits of adaptation

4.3.3.4.2 Trade-offs between adaptation pathways

4.3.3.4.3 Risk management and risk perception

4.3.3.4.4 Adaptation barriers and limits to 1.5 °C

4.3.4 Solar Radiation Management

4.4 Sectoral and regional implications of transitions and transformative pathways

4.4.1 Assessment framework

4.4.2 Sectoral implications of 1.5 °C pathways

4.4.2.1 Energy (including electricity)

4.4.2.2 Industry (including waste/recycling)

4.4.2.3 Transport

4.4.2.4 Buildings

4.4.2.5 Land: agriculture, livestock, forestry

4.4.2.6 Water

4.4.2.7 Food

4.4.2.8 Services (incl. health, education)

4.4.2.9 Air quality

4.4.3 Regional and local implications

4.4.3.1 Regional

4.4.3.2 National

4.4.3.3 Sub-national

4.4.3.4 Other scales will be identified through literature review

4.4.4 Assessment of global implications of pathways

4.4.4.1 Assessment of SSP models – global

4.4.4.2 Assessment of non-SSP models

4.4.4.3 Spill-overs, distribution, cost, benefits/“cost-benefits” and co-benefits analysis (adaptation and mitigation)

4.4.4.4 Macro-trends and interactions

4.5 Strengthening Implementation

4.5.1 Socio-economic

4.5.1.1 Introduction

4.5.1.2 Economic impact and economic tools

4.5.1.3 Ethics, justice and values

4.5.1.4 Social impact (employment, development, health, etc.) and acceptance including other non-economic impact (biodiversity, culture, values)

4.5.2 Lifestyle and behavioural change (Linda, Paolo)

4.5.3 Governance, institutions, capacity for change and politics

4.5.4 Policy instruments (Sabine, Seth, Paolo, Mustafa, James)

4.5.4.1 Mitigation

4.5.4.2 Adaptation

4.5.4.2.1 Paris Agreement and strengthening adaptation implementation

4.5.4.2.2 Strengthening adaptation implementation at regional to local scales

4.5.5 Finance

4.5.6 Technology transfer and innovation (Heleen, Marcos, Taishi, Seth)

4.5.7 Integration and summary

4.6 Conclusions

References

Chapter 5: Sustainable Development, Poverty Eradication and Reducing Inequalities

Box 5.4: Case studies: Bolsa Verde, Transitions Towns, Urban Innovations, Indigenous communities in the Arctic, and others…

5.6 Synthesis and Research Gaps

References

Chapter 1: Framing and Context

Coordinating Lead Authors: Myles Allen (UK), Opha Pauline Dube (Botswana), William Solecki (USA)

Lead Authors: Fernando Aragón-Durand (Mexico), Wolfgang Cramer (France), Mikiko Kainuma (Japan), Jatin Kala (Australia), Natalie Mahowald (USA), Yacob Mulugetta (UK), Rosa Perez (Philippines), Graciela Raga (Mexico), Morgan Wairiu (Solomon Islands), Kirsten Zickfeld (Canada)

Contributing Authors:

Review Editors: Ismail A. Elgizouli (Sudan), Andreas Fischlin (Switzerland), Xuejie Gao (China)

Date of Draft: 09/04/17

Executive Summary

1.1 Human, ecological, and physical dimensions of 1.5 °C: Building a knowledge base for this report

In December 2015, the *Paris Agreement* was negotiated by representatives of 195 countries at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) to undertake ambitious efforts towards mitigation of greenhouse-gas emissions, adaptation and finance, to start in 2020. The Agreement stresses the need of early action on greenhouse gas emissions with the objective of "holding the increase in the global average surface temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C". Furthermore, the Agreement establishes the global goal of "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change" and contains important signals that fast implementation of technical and policy measures to cut emissions will require adequate and opportune financing, transfer of technology and the identification of actions that would be beneficial for the climate, health and food security, while supporting sustainable development. This report directly responds to this charge and is designed to provide the knowledge base for this effort. This framing chapter provides the conditions and parameters of this knowledge base and assesses the unique opportunity for synergistic actions to achieve the goals of the Paris Agreement within the context of sustainable socio-economic development, poverty reduction and a substantive transformation of society.

The year 2015 also brought about extraordinarily significant advances to shared global challenges and to a self-realization that may pave the way to solutions. The realization that the world is now formed by socio-ecological systems and that we may have entered a new geological epoch, the Anthropocene, defined by unprecedented human influence on natural systems attested by e.g. climate change. This report scientifically assesses the effects and impacts that the world will face when the global surface temperature reaches 1.5 °C above pre-industrial level and seeks to strengthen the global response to this challenge in the context of sustainable development, poverty eradication, justice, equity and ethics. The results of this assessment provide ample evidence for an urgent need for action.

Previous IPCC reports have explicitly demonstrated evidence of human interference in the climate system to an extent that the average global surface temperature has reached approximately 1 °C above pre-industrial levels (IPCC 2013), while individual monthly average temperatures of 1.4 °C above these same levels have been observed. This increase has generated observed impacts (Chapter xx, Section xxx) and acts as an amplifier of risks for natural and human systems (Chapter xx, Section xxx), motivating early action to at least limit the rise in global temperatures to 1.5 °C above pre-industrial levels. Some regions of the world have locally experienced higher warming already, at different periods, but this should not be confused with a global temperature of 1.5 °C above pre-industrial levels (Chapter xx, Section xxx below). However, increases in extreme weather events, droughts, floods, sea level rise and biodiversity loss are already affecting economic development worldwide (Chapter xx, Section xxx). This is mostly in the developing world where this has to some extent been linked to migration and poverty. Small islands and populations residing in megacities, coastal regions and in high mountain ranges are some of the most affected.

Over the last two decades economic growth has been accompanied by increased life expectancy, educational attainment and income, but many regions are still subject to severe inequity in income distribution that amplifies vulnerability to climate change. The world population continues to rise and is projected to reach 9.7 billion by 2050 (United Nations 2015) with much of this growth occurring in hazard-prone small and medium sized cities in low and moderate income countries (Birkmann et al. 2016). This combined with other challenges such as conflicts, low development and challenges of globalization will act together with the threat of 1.5 °C above pre-industrial levels to exacerbate problems of food security and access to fresh water in different regions (FAO et al. 2015; Campbell et al. 2016). Recognizing these impacts and vulnerabilities has come with the realization that adaptation is pertinent and, more importantly, that it is not possible to separate climate change from development.

In the context of rapid, global urbanization, cities and everyday urban life embody both significant challenges and solution spaces for 1.5 °C efforts. Using urbanization as an example, there is a clear trend in the migration of populations towards large urban centers in many regions (e.g. LAC is 79% urban) and by 2050 urban dwellers will reach 80% of global population (United Nations 2015). The deterioration of air quality in megacities affect human health, already stressed by urban heat island effects (World Health Organization 2016). As a result, in the context of rapid, global urbanization, there is a need for an integrated framework of coordinated management of climate and air quality mitigation, recognizing that integrated policies can significantly reduce the cost of achieving objectives related to both areas. In particular, the transportation sector in megacities is “primed” for undergoing a transformative change to low- or no-carbon emissions that will result in a substantial improvement in the health and quality of life of hundreds of millions. Energy generation to cover the demands of urban populations is a huge sector also with a high potential to transition to low-carbon transformation. Similarly, sewage and the solid waste offer another climate mitigation opportunity in the path to sustainable development, justice and ethics in megacities.

The understanding of 1.5 °C comes from a variety of established and emergent knowledge bases. These different knowledges together will be critical to more fully realize the texture and conditions of impact, vulnerability, mitigation and the strengthening of the sustainable development agenda. The demands of the 1.5 °C challenge and conditions to define meaningful solutions requires this approach.

1.2 Understanding 1.5 °C; reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5 °C and 2 °C for use in this report

While the overall intention is clear, the Paris Agreement does not specify precisely what is meant by “global average temperature” relative to “pre-industrial levels.” Whether or when global temperatures reach 1.5 °C depends to some extent on these definitions. While the ultimate decision on what definition to adopt is beyond the scope of this report, working definitions are required to ensure consistency across chapters and figures. Issues affecting the definition include the choice of pre-industrial reference period, whether 1.5 °C refers to total or human-induced warming, and which variables and coverage are used to define global average temperature change. In this section, a definition is proposed and related to various potential alternatives.

1.2.1.1 Choice of variable

The IPCC has traditionally defined changes in observed global average temperature as the average of northern and southern hemispheric changes, each compiled as an area-weighted average of observed near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Hansen et al. 2010; Morice et al. 2012). This report assumes that this practice will continue, but with improved data coverage in Arctic and Antarctic regions. Modeling studies, with no coverage constraints, have typically used a simple area average of SAT over land, sea-ice and oceans. For relatively low warming levels, the difference can be significant: Cowtan et al. (2015) show that the use of blended SAT/SST data gives approximately 0.1 °C less warming to date in the CMIP5 ensemble than the use of area-average SAT, while Richardson et al. (2016) show that incomplete coverage reduces warming to date by a further 0.1 °C (see inset panel in Stocker et al. (2013), figure TFE8.1 and Figure 1.1). Detection and attribution studies have generally been careful to make a like-for-like comparison, accounting for coverage (Tett et al. 1999; Jones et al. 2003). The simple climate models used in many Integrated Assessment Models do not distinguish SAT and SST, but are typically calibrated to more complex models or observations, and hence could reproduce either a pure SAT or blended SAT/SST metric. Richardson et al. (2016) show that defining global temperature using a blended SAT/SST metric reduces the expected transient warming under rapidly increasing forcing by approximately 10% relative to a pure SAT metric, but is not expected to impact the equilibrium response.

[INSERT FIGURE 1.1 HERE]

Figure 1.1: Evolution of global warming over the observed period. Warming is expressed as anomalies from the 1861-1880 base period (green shading) for monthly means of the HadCRUT4, NOAA and GISS datasets, which measure a blended mix of near surface air temperature over land and sea surface temperature over oceans. Human-attributable warming (orange) and naturally-forced warming (blue) are calculated using the two time constant response model of Myhre et al. (2013) following Otto et al. (2015). Proportional uncertainty in the final human-attributable warming is set equal to that from Bindoff et al. (2013). The purple lines show the modelled global-mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 ensemble under the Historical and RCP8.5 scenario.

1.2.1.2 Choice of reference period

Any choice of reference period represents a compromise between data coverage and representativeness of pre-industrial conditions. In this report, we propose, where possible, to use 1861-80, as used in the carbon budget calculations in AR5 (e.g. figure SPM10 of IPCC (2013) and Table 2.2 of the IPCC (2014a)), representing the earliest period for which near-global observations are available that was not subject to strong volcanic activity. Years after 1880 are subject to strong but very uncertain volcanic forcing, complicating their use in a reference period. Temperatures rose by approximately 0.1 °C over the century prior to 1861, but less than half of this warming is estimated to be anthropogenic.

1.2.1.3 Total, expected or human-induced warming

Total warming refers to the actual temperature change, irrespective of cause; expected warming excludes random or unpredictable natural climate fluctuations; and human-induced warming refers to the component that is attributable to human activity. Total warming is timescale-dependent: temperatures in individual years can fluctuate substantially around the long-term expected temperature due to externally driven and internally generated climate variability. While recognizing that many systems are impacted by total changes, irrespective of cause, studies of climate change impacts typically refer to warming levels defined by multi-decade average temperatures, consistent with the traditional WMO definition of “climate”, which is approximately equal to expected warming.
Mitigation studies focus on human-induced warming because, while natural drivers may be included in historical simulations used to initialize them, possible future natural fluctuations, either internally generated or externally forced, are neglected as both unpredictable and unaffected by mitigation policy. Given that overall warming due to changes in solar and volcanic activity from 1861 to present is small, there is little practical difference between expected and human-induced warming. This equivalence would need to be reconsidered should a predictable secular trend in natural forcing emerge in future, but there is no evidence for this at present. Hence, for the purposes of this report, a “1.5 °C world” is defined as one in which expected temperatures are 1.5 °C above the pre-industrial reference period or, practically equivalently, in which human-induced warming has reached 1.5 °C.

On this definition, global temperatures would fluctuate equally on either side of 1.5 °C above the reference period in the absence of a large volcanic eruption (which would cause temporary cooling). Alternative definitions, such as maintaining the probability of temperatures fluctuating over 1.5 °C below a specified level, are more ambiguous, since they depend on the averaging timescale used and the properties of future natural variability. An indication of the range of natural fluctuations is given by Figure 1.1, which shows observed 20-year-average temperatures varied by ±0.1 °C (5-95% range), and monthly temperatures by ±0.2 °C, around the human-induced warming trend over the period 1861-2017. Regional fluctuations would be larger still.

1.2.1.4 Summary

For the purposes of this report, warming relative to pre-industrial levels is defined as the increase in expected global average blended surface air temperature changes over land and sea surface temperature changes over oceans, relative to the reference period 1861-80, and assuming full spatial coverage in future (extending past coverage would exclude rapidly-warming polar regions).

1.2.2 Global versus regional and seasonal warming

Warming is not observed or expected to be spatially uniform, nor distributed uniformly across all months of the year (IPCC 2013). This is illustrated by Figure 1.2, which shows a best-estimate of the observed change in seasonal average temperatures in the June-August and December-February seasons, associated with the observed 1 °C rise in global temperatures relative to the 1861-80 reference period. Many regions, particularly in northern mid-latitude winter, have already experienced regional warming in excess of 1.5 °C or even 2 °C. Natural climate fluctuations mean that individual seasons may be substantially warmer, or cooler, than these expected long-term average changes [perhaps add some text on magnitude and timescales of unpredictable regional climate fluctuations, e.g. Deser et al. (2012), in the FOD].

[INSERT FIGURE 1.2 HERE]

Figure 1.2: Regional human-attributable warming in 2016 relative to 1861-1880 for the average of December, January and February (DJF – left) and for June, July and August (JJA – right). Trends are evaluated by regressing regional changes in the HadCRUT4 dataset onto the human-attributable warming (orange line in Figure 1.1). Data is shown where missing data represents less than 50% of the record. Hatching indicates significance of linear trends at a 10% confidence level assuming Gaussian errors.

1.2.3 Definition of 1.5 °C consistent pathways and associated emissions

The Paris Agreement does not associate a timescale or pathway with the long-term temperature goal, so classifying temperature pathways that might be considered consistent with 1.5 °C is an important task for this report. Three broad categories of temperature pathways are used in this report, associated with very different impacts and emissions: temperature stabilization, continued warming, and temperature overshoot.

1.2.3.1 Temperature stabilization pathways

The simplest 1.5 °C-consistent pathway is one in which human-induced warming rises monotonically to stabilize on 1.5 °C. Because of the inertia of the climate, carbon cycle and energy systems, the rate of human-induced warming varies slowly over decades, allowing only smooth temperature pathways if temperature goals are achieved through emission reductions alone. Given human-induced warming is currently approximately 1 °C and increasing at almost 0.2 °C per decade, a reduction in this rate of warming at an average rate of 4% per year from now on is required to stabilize temperatures at 1.5 °C without overshoot (see Figure 1.3). Sea-level rise would continue after temperature stabilization, albeit at a decreasing rate.

Stabilization has often in the past been used to refer to stabilization of atmospheric greenhouse gas concentrations, which would result in continued warming over multi-decade to centennial timescales. In view of the focus on temperature goals, this report will focus on temperature rather than concentration stabilization scenarios, but the word stabilization will be qualified where necessary to avoid confusion.

1.2.3.2 Temperature overshoot pathways

Under this category of pathway, temperatures rise above 1.5 °C before peaking and declining, either to converge on 1.5 °C from above or to fall below it. Substantial negative emissions (anthropogenic removals) are required to draw temperatures down, so their feasibility and availability limit accessible rates of temperature decline. In this report, consistency with the Paris Agreement temperature goal is interpreted as implying temperatures peaking well below 2 °C. Overshoot pathways are referred to in this report as 1.5 °C-consistent, but qualified by the amount, duration and timing of the temperature overshoot, which can have a substantial impact on sea level rise and many irreversible climate change impacts such as species extinctions.

1.2.3.3 Continued warming pathways

Under this category, 1.5 °C is reached and temperatures then continue to warm. Impacts may be very different from a 1.5 °C temperature stabilization scenario, particularly if warming is relatively rapid, since surface temperatures are not in equilibrium with atmospheric composition. In particular, CO_2 concentrations will be higher under a continued warming scenario when temperatures reach 1.5 °C than they would be under a temperature stabilization scenario, leading to very different ecosystem and agricultural impacts. While continued warming scenarios are widely used to assess the impacts of 1.5 °C because of the lack of available temperature stabilization scenarios, they are not referred to in this report as 1.5 °C-consistent pathways.

An important sub-category of continued warming pathways are baseline scenarios, in which either no climate mitigation policies are assumed at all, or existing climate mitigation policies and commitments are extrapolated into the future. A distinction must be drawn between "efficient" baseline scenarios, in which resources are deployed efficiently in the future without regard to their climate impact, and "business-as-usual" scenarios in which current trends and policies are extrapolated. The distinction is important because mitigation scenarios typically assume efficient resource allocation subject to a climate constraint, so an efficient baseline is needed for a like-for-like comparison.

[INSERT FIGURE 1.3 HERE]

Figure 1.3: Schematic showing categories of temperature pathways, with associated CO_2-equivalent emissions, cumulative emissions and sea-level-rise from a semi-empirical model (Kopp et al. 2016).

1.2.3.4 Precautionary versus adaptive mitigation scenarios

A useful distinction can be drawn between precautionary mitigation scenarios, in which emissions are prescribed to achieve a temperature goal at a given level of probability, such as maintaining temperatures below 1.5 °C with 66% probability given current uncertainties in the climate response, and adaptive mitigation scenarios, in which it is assumed that emissions are actively adjusted in future to meet the temperature goal in the light of the emerging climate response. In precautionary scenarios, emissions are prescribed and the uncertainty is in the climate response. Uncertainty in the transient climate response alone means that the most likely warming in a precautionary "66% chance below 1.5 °C" scenario is around 1.2 °C, while there is still a non-negligible probability of temperatures exceeding 2 °C. In adaptive scenarios, the uncertainty is in future emissions rather than future temperatures (including whether potentially required rates of emission reductions are achievable), so the temperature outcome is effectively certain, apart from natural climate fluctuations. Impact studies implicitly assume adaptive mitigation, because they consider the implications if the temperature goal is actually met, rather than undershot at a given level of probability, while the majority of mitigation studies to date have taken a precautionary approach to scenario development.

1.2.3.5 Cumulative emission budgets

The AR5 drew attention to the fact that there is a simple, near-linear relationship between cumulative CO_2 emissions and CO_2-induced warming (Allen et al. 2009; Matthews et al. 2009; Zickfeld et al. 2009), characterized by the Transient Climate Response to Emissions, or TCRE. At that time, the notion of a cumulative carbon budget could not be extended to non-CO_2 agents because the majority of these are relatively short-lived climate pollutants (SLCPs) and hence do not accumulate in the climate system. Allen et al. 2016, drawing attention to a point made implicitly in Shine et al. (2005), observe that an equivalence can be drawn between cumulative emissions of CO_2 and changes in emission rates of SLCPs, which opens the possibility of a cumulative CO_2-equivalent emission budget consistent with different levels of warming and a given value of the TCRE.

1.2.4 Definition of "balance" and net zero emissions

Article 4 of the Paris Agreement acknowledges that, "in order to achieve the long-term temperature goal … Parties aim to … achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…" This report will clarify what is meant by "balance" in the context of 1.5 °C.

For CO_2 alone, the interpretation of "balance" is unambiguous. On multi-century timescales, natural processes that remove CO_2 permanently from the active carbon cycle are so slow that balance means net zero global anthropogenic CO_2 emissions (Archer and Brovkin 2008; Matthews and Caldeira 2008; Solomon et al. 2009). Net zero emissions means that any remaining anthropogenic CO_2 emissions will need to be compensated for by an equal rate of anthropogenic CO_2 removal, using measures such as bioenergy with carbon capture and sequestration (BECCS), large-scale afforestation, biochar enhanced soil sequestration, direct air capture or ocean alkalinization. On shorter timescales, CO_2-induced warming also remains approximately constant for many decades after achieving net zero anthropogenic CO_2 emissions because of compensation between continuing adjustments in the climate system and carbon cycle (Section 1.2.5), but other aspects of climate would not be constant: sea level would continue to rise and ocean alkalinity would begin to recover.

For other greenhouse gases, "balance" need not necessarily be interpreted as implying zero anthropogenic emissions at the level of individual gases. Sustained emissions of a greenhouse gas at a rate (in tonnes per year) a few percent below the excess atmospheric load above pre-industrial levels (in tonnes) divided by the gas lifetime (in years) is consistent with gradually declining atmospheric concentrations (Shine et al. 2005; Rogelj et al. 2015; Schleussner et al. 2016) and no additional contribution to warming. Because it is inversely proportional to the gas lifetime, this "balanced" emission rate may be substantial for a short-lived climate pollutant (SLCP) such as methane, but is near zero for a long-lived or cumulative pollutant such as nitrous oxide. Note that this requires the interpretation of "balance" to include natural sinks. Even though a constant emission of an SLCP might not be contributing to additional warming, it could still represent a mitigation opportunity, since reducing it would lead to a near-term cooling.

For a combination of gases, if "balance" is interpreted as reducing the rate of human-induced warming (currently about 0.18 °C per decade) to zero, which is required for temperatures to peak any level, it requires near-zero net emissions of long-lived pollutants (CO_2 and gases with lifetimes of a century or more, such as nitrous oxide) over multi-decadal timescales, such that any residual anthropogenic sources of these gases would need to be balanced by anthropogenic removals of an equivalent amount (in terms of their impact on temperature) of other long-lived pollutants. It also requires constant net emissions of SLCPs, such that any increase in emission rate of one SLCP would need to be compensated for by an equivalent decrease in emission rate of another SLCP. Within (but not between, for reasons given in Smith et al. 2012, and Daniel et al. 2012) the categories of long-lived pollutants and SLCPs, equivalence can be defined to a reasonable approximation using the standard GWP100 metric (Allen et al. 2016, and see Box 1.1). An increasing rate of net emissions of SLCPs could be compensated for by net negative emissions (anthropogenic removals) of long-lived pollutants and still yield stable temperatures, but compensating for substantial continued net emissions of long-lived pollutants with continually falling emissions of SLCPs would not be possible, since it is impossible to reduce the rate of emission of most SLCPs below zero (with the possible exception of methane – see Boucher and Folberth 2010).

[START BOX 1.1 HERE]
Box 1.1: Long-lived and short-lived climate pollutants and emission metrics
[END BOX 1.1 HERE]

Another interpretation of Article 4 might be that sources and sinks of greenhouse gases balance in such a way that the equivalent atmospheric CO_2 concentration is stabilized. However, stabilization of CO_2-equivalent concentration implies continued warming (see Section 1.2.5) which is not consistent with a focus on temperature goals.

Should temperatures exceed 1.5 °C, then returning them to 1.5 °C would require the rate of human-induced warming to pass through zero and become negative. For this to occur, emissions would need to be reduced below the net zero level implied by this interpretation of "balance", through some combination of anthropogenic removals of long-lived pollutants and falling anthropogenic emissions of SLCPs. Hence achieving "balance" in the sense described here represents a necessary, but potentially not a sufficient, condition for achieving the 1.5 °C temperature goal.

1.2.5 Definitions of warming commitment

The question of whether the 1.5 °C target is attainable implicitly includes the notion of warming "commitment", or unavoidable future warming. This arises due to inertia in the physical Earth system, but also due to technological, economic, institutional and behavioral inertia.

Geophysical warming commitment is defined as the unavoidable future warming from past anthropogenic emissions of greenhouse gases (GHG) and aerosol precursors. It is also referred to as "zero emissions commitment" in the literature (Gillett et al. 2011; Matthews and Caldeira 2008; Matthews and Zickfeld 2012; Plattner et al. 2008; Zickfeld et al. 2013), as it can be quantified in climate model simulations by setting future GHG emissions to zero. The magnitude and sign of the geophysical warming commitment depend on the gas because of different atmospheric lifetimes and signs of radiative forcing. For CO_2, which has an atmospheric lifetime of centuries to millennia (Eby et al. 2009), the geophysical warming commitment ranges from slightly negative (i.e. a slight cooling after emissions cease) to zero, implying no future warming from past CO_2 emissions (Gillett et al. 2011; Matthews and Zickfeld 2012). This near-zero warming commitment for CO_2 arises from the near cancellation between declining radiative forcing in response to the elimination of CO_2 emissions (cooling effect) and the delayed temperature response to previously increasing radiative forcing from CO_2 (warming effect) (Solomon et al. 2009).

A widely discussed variant is the "constant composition commitment" (Meehl et al. 2005, 2007), which is the remaining warming if atmospheric composition and hence radiative forcing were stabilized at the current level. This is less policy-relevant, because maintaining constant atmospheric composition would require a specific combination of non-zero emissions that does not correspond to any scenario.

For greenhouse gases with a short atmospheric lifetime (order decades or less) such as methane (CH_4) the warming commitment is negative, implying cooling if future emissions of these gases are eliminated. This cooling arises from a rapid decline in radiative forcing, which dominates over the delayed warming response to previously increasing radiative forcing. Substances with a short atmospheric lifetime and negative radiative forcing such as sulphate aerosols have a positive warming commitment, as elimination of the radiative "dimming" effect of these substances results in rapid warming over about a decade. Estimates of the warming commitment from sulphate aerosols is uncertain due to large uncertainties in radiative forcing (Myhre et al. 2013). Using a range of sulphate aerosol radiative forcings consistent with temperature observations, Matthews and Zickfeld (2012) estimate a total geophysical warming commitment from GHGs and sulphate aerosol emissions up to year 2010 of about 0.3 °C (0.25-0.5 °C) over the decade immediately following elimination of emissions, although about half of this additional warming persists for only a few decades.

Geophysical warming commitment can be thought of as the minimum warming commitment, absent inertia in the socio-economic system (i.e. the future warming we could expect if we were to eliminate all GHG emissions tomorrow). However, existing infrastructure, institutions, and behavioral and social norms constrain the rate and magnitude of future GHG emission reductions. Three main types of inertia in the socio and techno-economic system have been identified in the literature: infrastructural and technological, institutional, and behavioral (Seto et al. 2016). Infrastructural and technological inertia arises from the long lifetime and large investments associated with energy infrastructure. Unless power plants will be retrofitted with carbon capture and sequestration (CCS) or operable infrastructure decommissioned early, existing infrastructure can be expected to contribute CO_2 emissions and warming for many decades. Davis et al. (2010) estimate 0.2-0.5 °C future warming from existing GHG emitting energy infrastructure (as of 2009), confirmed and updated by Pfeiffer et al. (2016).

In contrast to infrastructure and technological inertia, "institutional inertia is an intended feature of institutional design, not an unintended by-product of systemic forces" (Seto et al. 2016). Institutional inertia arises because "powerful economic, social, and political actors seek to reinforce a status quo that favors their interests against impending change or to create and then stabilize a new, more favorable, status quo" (Seto et al. 2016). The transition to a low-carbon trajectory is also hampered by behavioral inertia. Two factors contribute to this inertia: psychological processes and social structure. Habits, aversion to take risks and the necessity of collective action to solve the climate change problem (giving the feeling to individuals that they have little control over the problem) can lock in carbon intensive behaviors (Seto et al. 2016). Also, individual behavior is embedded in social norms and processes that change only slowly in response to changes in the technological and political environment (Seto et al. 2016).

1.3 Multiple dimensions of impacts at 1.5 °C and beyond

The impacts of climate change throughout the world are projected to be uneven and very localized. Impacts are consequences not only of rising temperatures and sea level, but also shifting trends in rainfall patterns, extreme events and physical impacts such as floods, droughts, and heat waves (IPCC 2012, 2014b). Impacts of climate change occur across the regions of the global and affect sectors including natural ecosystem and managed systems, urban and rural areas, economic services, human health, livelihoods and poverty, and human security (IPCC 2014b). Many impacts have been formally attributed to global warming and the increasing greenhouse gas concentrations due to human activities, but other forcings play major roles, such as land use change, atmospheric pollution and others.

The reference to 1.5°C is a decision made in the context of UNFCCC negotiations; but what do we mean when we say impacts of 1.5°C? Differentiating it from 2°C does not imply a scientific statement of safe vs. unsafe environmental conditions. For example, Schleussner et al. (2016), assessed the differential impacts of 1.5 °C and 2°C and concluded that for heat-related extremes, the additional 0.5°C increased global warming represents the upper limit of current natural variability and a new climate norm, particularly in tropical regions. For this Special Report, we propose that "impacts at 1.5°C' refers to the impacts when the expected global average of near-surface air temperature is 1.5° degrees above a pre-industrial period subject to similar natural forcing."

Impacts are multi-dimensional; hence, there is no universal, value-neutral metric of impact. While some of these dimensions are obvious (space, time, sector), others are less so (probability, equity, anthropocentricity), but they are all relevant to the climate discussion. This multi-dimensionality is particularly important for 1.5 °C and 2 °C because at these levels of warming, impacts may still be very small or even positive when measured along certain dimensions. The weight assigned to different dimensions could eventually affect the sign of the aggregate or total impact. For example, estimating the impacts of sea-level rise on property value would depend heavily on whether some form of "equity weighting" is applied to the total monetary value, or aggregate total loss.

[INSERT FIGURE 1.4 HERE]

Figure 1.4: Place holder for a Schematic diagram to illustrate the point, e.g. heat wave risk as an example of an impact that increases more rapidly with warming, while mid-latitude extreme precipitation risk increases approximately linearly, because of the different shapes of the tails of the temperature and precipitation distributions.

1.3.1 Detection and attribution of impacts

Observed impacts may be attributed formally to various climate drivers. While objective detection and attribution techniques are commonly used within the physical climate sciences to attribute the likelihood of particular events to anthropogenic warming (e.g., Stott et al. 2004), detection and attribution can also come from more subjective forms of knowledge, such as community knowledge of impacts. These types of knowledge are equally important and need to be considered within the context of a 1.5 °C world, but the challenge is how to include multiple forms of knowledge. Although a region may not be classified as being impacted from a climatological perspective, local community knowledge of impacts (i.e., subjective) is equally important (Brinkman et al. 2016; Kabir et al. 2016). That is, there are many drivers of “impact experience”.

1.3.2 Physical Dimensions of Impacts

1.3.2.1 Spatial and temporal distribution of impacts

The spatial and temporal distribution of impacts are key considerations in understanding what 1.5 °C impacts mean for people. Several regions are already 1.5 °C warmer with respect to the pre-industrial period (Figure 1.2). Therefore, local impacts of a global mean warming of 1.5°C can well be higher (or, in fewer instances, lower) than 1.5°C globally.

Intertwined with the spatial distribution of impacts is the temporal aspect (IPCC 2013). The time of occurrence of 1.5°C above pre-industrial levels will vary for different regions, with some regions, for example parts of Africa, warming faster (Niang et al. 2014; Déqué et al. 2016). This raises adaptation and intergenerational issues. Also, the seasonal cycle of temperature or rainfall will change, as projected for Mediterranean climates. At global warming of 1.5 °C, some seasons will be substantially warmer than 1.5 °C above pre-industrial, for example the southwest of Western Australia (Andrys et al. 2016), which experiences a typical Mediterranean climate.

1.3.2.2 Implications of 1.5 °C for extreme events and associated impacts

Warming by 1.5 °C has very important implications for changes in extremes at the tail of the event probability distribution. Any increase in the global mean temperature implies a much larger probability of temperature extremes. Specifically, a 1.5 °C world as compared to a 2 °C world will have very different impacts in terms of extreme events. This report further builds on IPCC SREX report by specifically examining the impacts of 1.5 °C versus 2 °C of warming with respect to weather and climate extremes.

[INSERT FIGURE 1.5 HERE]

Figure 1.5: Placeholder for schematic showing differences in tails of the temperature distribution for a 1.5 °C versus 2.0 °C world.

1.3.2.3 Non-temperature related impacts

Although the focus of this special report is on 1.5 °C of warming, it is important to acknowledge that not all impacts depend on warming alone, e.g., sea-level rise and ice-sheet melt depend on integrated temperature. Hence, some climate studies use the concept to the “degree year”, which is generally defined as the time integral over which the amount of global mean temperature exceeds a threshold, which has been adjusted for climate sensitivity (Smith and Rasch 2013). Such metrics are particularly relevant to overshoot scenarios. Other impacts also depend on atmospheric composition and forcing (e.g., ocean acidification and some extreme temperature and rainfall indices). Additionally, it is important to contrast temperature-related impacts (e.g. annual rainfall, extreme events) with impacts due to integrated temperature (e.g. ice-sheet melt and sea level rise). For example, some of the non-temperature impacts manifest earlier under transient warming, some are irreversible (i.e. species extinction) and others can be reversed to some extent.

1.3.2.4 Probability and uncertainty of impacts

This section will briefly discuss what the definition of 1.5 °C used in this report (defined in earlier section) implies in terms of probability and uncertainties associated with impacts.

1.3.2.5 Deterministic (e.g. sea level rise) versus stochastic (e.g. extreme weather) impacts

The capacity and conditions for modeling future physical climate impacts varies significantly. Deterministic models define potential conditions of gradual and uni-directional climate-related changes while stochastic models are used to construct estimates of future frequency for more acute and likely high consequence events such as extreme weather events, including cyclonic storms, intense precipitation events, and extreme heat events. The different modeling domains present a range of uncertainty measures and likelihood conditions that must be recognized when examining climate conditions under 1.5 °C and the difference between 1.5 °C and 2 °C.

1.3.2.6 Permanence and irreversibility

Conditions of permanence and irreversibility are two key parameters of physical climate impacts.

1.3.3 Human Dimensions of Impacts, including adaptive capacity

The adaptive capacity of different sectors to a 1.5 °C world will vary markedly between different sectors, for example, water supply, public health, infrastructure, ecosystems, food supply. Additionally, the adaptive capacity of human settlements, especially in highly populated urban regions poses several equity and social justice issues.

1.3.3.1 Sectoral impacts

The climate change impact of 1.5 °C will affect a range of infrastructure systems and the built-up environment, natural resources development and provisions capacities, as well as agricultural production systems. Climate related shifts including changes in seasonality, temperature regimes, and water availability have resulted in a variety of documented effects. The sensitivity of human systems to these changes to a 1.5 °C world as well as 2 °C is investigated in this report.

1.3.3.2 Spatial and temporal dimensions

The human system impacts vary temporally and spatially under conditions of a 1.5 °C world. Some parts of the globe have already experienced over 1.5 °C of regional warming. Given the vulnerability of some sites, these impacts result in intergenerational consequences.

1.3.3.3 Human settlements

The magnitude and consequences of climate impacts vary across the range of human settlement types. Density and risk exposure, infrastructure vulnerability and resiliency, and governance capacity drive the differential impacts. Global scale urbanization places significant stress on capacity of cities to respond to climate risk, especially in small and medium sized cities in low and middle income countries where rate of population growth and climate exposure is especially significant.

1.3.3.4 Poverty, equity and justice

Climate change impacts disproportionately affect the most vulnerable segments of society. These populations, communities, and institutional often lack adaptive capacity to increased climate risk and new or emergent risks.

1.3.4 Ecosystem Impacts

Temperature-related (e.g. precipitation); integrated temperature (e.g. ice-sheet melt) and non-temperature-related (e.g. ocean acidification).

1.4 1.5 °C in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, with consideration for ethics and equity

The connection between 1.5 °C warming and ambitions of sustainable development are complex and multifaceted. This connection can be better understood from mitigation-adaptation linkages, synergies and trade-offs and the different dimensions of feasibility. IPCC AR5 acknowledged that "adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses" (Denton et al. 2014). A goal of this report is to articulate where the key tradeoffs and opportunities for synergy are present. Adequate mitigation and adaptation measures and actions can be put into place by identifying specific patterns of development and governance that indeed differ amongst all world regions. This section details the various implementation options, enabling conditions, capacities and types of knowledge that can allow institutions, communities and societies at large to respond to the 1.5 °C challenge in the context of sustainable development. Issues of justice, equity and ethics are recognized as of paramount importance to reduce vulnerability and eradicate poverty. The section begins by highlighting the four dimensions of feasibility with respect to global warming of 1.5 °C.

1.4.1 The different dimensions of "feasibility"

Reaching the target of only a 1.5 °C rise in temperature remains a challenging task, which will be constrained by several dimensions of feasibility. The report defines the feasibility as the systems-level capacity to achieve a specific goal or target. The term does not explicitly incorporate uncertainty and likelihood and assesses all other things equally would a particular outcome be possible. From an energy balance perspective, certain temperature targets are "physically feasible", depending on the concentrations of CO_2 and other radiatively important aerosols and gases (IPCC 2013). In addition, more aggressive pathways will require new technology that may or may not be "technically feasible" (IPCC 2014c; Rogelj et al. 2015). For policy makers, the "economic feasibility" is also important, and because of environmental damages from some proposals, some pathways may not be socially acceptable (Smith et al. 2016). There is also a need for a governance structure which allows for appropriate "institutional feasibility" for any policy to reach a particular temperature target (Planton 2013).

1.4.2 The adaptation-mitigation-sustainable development nexus: tradeoffs, synergies and co-benefits

Responding to climate change needs to occur using multiple approaches (Figure 1.6). From the mitigation side, the most important is to reduce emissions of CO_2 and other greenhouse gases (Planton 2013). Even if low CO_2 trajectories are achieved, there will be impacts of climate change onto humans and ecosystems, which will require adaptation (Planton 2013). It may be required that extreme measures be undertaken in order to avoid climate change, either through Carbon Dioxide Removal (CDR), whereby carbon dioxide is actively removed and stored (Rockström et al. 2016), or Solar Radiation Management (SRM), where deliberate changes to the earth's albedo are undertaken (The Royal Society 2009). Never-the-less there are mechanisms to respond to climate change that will enhance both mitigation and adaptation and with appropriate governance also provide for social justice, equity and ethics (Figure 1.6).

[INSERT FIGURE 1.6 HERE]

Figure 1.6: Schematic of some adaptation and mitigation options, showing examples of those that serve both to help adaptation and mitigation (figure needs to be redone for this report).

The impacts of climate change onto humans and ecosystems are not equally distributed, because some humans or ecosystems may be more vulnerable to climate change (Agard and Schipper 2014). For example, subsistence farmers are more sensitive to precipitation changes than farmers in regions with advanced irrigation techniques. The ability to adapt to climate change, or adaptive capacity, can build resilience to weather or other hazards (Agard and Schipper 2014).

At the same time as humans are responding to the challenges of climate change, the UN has also established the Sustainable Development Goals (SDG) (UN 2016) to be reached by 2030. The legacy of the goals will be carried forward into the next decades as well. The SDGs include the eradication of poverty, hunger and wars, gender and economic equity, improved health and education, access to clean water and environment, among other ambitious, yet vital goals. Some of these goals are likely to be enhanced by strong climate change response, but some SDGs may be more difficult to achieve with a strong climate mitigation response. For example, if bioenergy and carbon capture and storage is used for climate mitigation, this can place pressure on food security (Smith et al. 2016) or many strong mitigation pathways are expensive, thus reducing the likelihood of poverty eradication (Stechow et al. 2016).

Conversely, multiple examples of synergies exist between achieving SDGs and climate responses. For instance, converting to sustainable energies can enhance the energy security of a society and protect the ecosystem services offered by land and ocean environment. In addition, adaptive capacity and resilience is enhanced in societies with a broad access to education and infrastructure. Since urbanization is occurring at an accelerating rate, the interactions between urbanization, sustainable development and climate response needs to be considered. Simultaneously considering how to achieve an ambitious low climate trajectory and achieve the SDGs is a center point of this report (Figure 1.7). Intuitively, it is likely that addressing these multiple goals simultaneously is more likely to achieve a cost-effective and socially acceptable solution, than addressing these goals piecemeal (Stechow et al. 2016).

[INSERT FIGURE 1.7 HERE]

Figure 1.7: A framework for evaluating the impact of different climate response pathways on the multiple dimensions of the Sustainable Development Goals: needs to be edited for inclusion). For each goal, positive or negative impacts for each climate action can be estimated, highlighting the climate response pathways that require tradeoffs versus those that have the most synergies.

Common tools for making difficult policy decisions include cost-benefit analyses, whereby the costs of impacts are compared to the benefits from different actions (IPCC 2014c). However, for problems such as climate change or sustainable development these tools can be difficult to use because of the disparate impacts versus costs. For example costs may be relatively easily quantifiable in terms of money, but the impacts of climate change may be on humans lives, their culture and values or ecosystem impacts, which are difficult to quantify and compare (IPCC 2014c). In addition, costs and benefits can occur at very different times, even across different centuries, for which case, standard cost-benefit analyses become difficult to justify (IPCC 2014c).

1.4.3 Implementation and governance

The major challenge is transitioning from planning to practical implementation of identified climate responses and this is due to several barriers including finance, technology and human resource constrains plus institutional capacity to strategically deploy available knowledge and resources (AR5 Chapter 15). Uncertainties in climate change at different scales, different capacities to respond coupled with the complexities of social-ecological systems point to a need for diverse implementation options within and among different regions involving different actors. The tremendous regional diversity including highly carbon invested economies and emerging economies are important considerations for the 1.5 °C – sustainable development connection and equity. Key sectors such, as urban systems, food security and water supply also are critical to the connections. Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments and facilitating partnerships among public, civic, and private sectors will be key to implementing identified response options. Implementation options could be informed by Chapter 20 of IPCC AR5 key message that: "To promote sustainable development within the context of climate change, climate-resilient pathways may involve significant transformations. Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways" (Denton et al. 2014).

Policy arenas, governance structures and robust institutions are key enabling conditions for transformative climate action in enabling the global response to 1.5 °C warming. A range of high and some middle income cities provide examples of government and community response can simultaneously make meaningful contribution to adaptation and mitigation goals. Conversely, the risk of climate change will escalate in countries with severe governance failure (IPCC 2012; Oppenheimer et al. 2014; Revi et al. 2014) and climate change threat may also weaken governance e.g. triggering conflict or migration and deepening vulnerability (Voski 2016).

Adaptation incorporates changes on modes of governance. It is through governance that justice, ethics and equity within the adaptation-mitigation-sustainable development nexus can be addressed. This can be illustrated in cities where different management solutions can have implications for equity as is the case of the privatization of water supply and sanitation services (Revi et al. 2014). Governance is critical to the response to 1.5 °C warming given the diversity of organizations and actors at national and global level that have a role in the climate change challenge (Busby 2016). Governance capacity plays a critical role in a range of key contexts including the realization of the Intended Nationally Determined Contributions (INDCs), small island states, highly vulnerable sites, low carbon and zero carbon cities.

Solar radiation management strategies which press against socially acceptable and physical limits, provides another example of the constraints and capacities of governance with respect to decision-making equity, and integrating levels of uncertainty into the decision-making process.

1.4.4 Timescales and transformation

The pace and process of transformation is varied. The report recognizes that the rate of change within systems can occur gradually or be punctuated by rapid change. Incremental change can set in motion larger scale transformations. The debate on resilience-transformation, as this incremental process has been identified (e.g. in urban areas), is key when designing, planning, and improving implementation options at local level. The connection between climate action and sustainable development illustrates a complex coupling of systems that have important spatial and time scale lag effects. Early warning signals of system change provide important sign posts for potential transition pathways and of use by decision makers and policy makers.

1.4.5 Enabling an adaptive response to emerging trends and extreme events

A critical element defining the connection between 1.5 °C and sustainable development is the capacity of institutional actors to adaptively respond timely to new challenges and opportunities. Extreme events approached through disaster risk reduction can play a key role in motivating climate response with respect to financing, technology advancement and transfer, and capacity building and governance. Emerging trends and extreme events are utilized to building institutional capacities and human resource at local, national and global level to plan, implement and monitor climate responses.

1.4.6 Justice, equity and ethics

Poverty, inequity, and injustice are incompatible with sustainable development (O' Brien et al. 2012). As indicated by Stern 2014 and many others, the science informs us that the climate change is a problem of risk management on an immense scale; and the consequences of business-as-usual could significantly threaten human security i.e. amounting to the displacement of hundreds of millions of people that may lead to severe and prolonged conflict. Risks on this scale raise deep questions about ethical perspectives relating to the distribution of impacts associated with climate change and responsibilities for its cause, and preferentially impact on the poor and disenfranchised. Thus, focusing on the rights and responsibilities of people as the core policy question, rather than physical and ecological infrastructures, may help to clarify the root causes of climate risks, their distribution and management across a range of social groups and geographies. Human rights include the right to development, equitable benefits and burdens, participatory, transparent and accountable decisions on climate change, gender equity, and education rights.

Questions of justice and fairness are central to climate change debates and response efforts across geographies and generations. Most fundamentally, how can the action to achieve 1.5 °C targets be consistent with protection of human rights? Okereke (2010) outlines three key points of connection between climate change and justice from the international regime (UNFCCC) perspective. The first is the asymmetry in contributions to the problem. The second is the huge asymmetry in impact – a problem that is exacerbated because the worst impact tends to fall on those that are least responsible for the problem. Conditions of climate dislocation are an acute example of this inequity and forced migration. Intergenerational equity issues also need to be considered here. The third point of connection in the climate-justice nexus is asymmetry in power to decide solutions and response strategies. This relates to the possibility by the more powerful actors and stakeholders to have greater influence on setting the agenda to their advantage. Hence a justice framing offers a useful organizing framework for understanding the asymmetry between the distributions of benefits and distribution of costs in relation to climate change. In addition, existing inequalities, technology, finance, human capital and governance constrain any level approach to addressing the 1.5 °C despite e.g. INDCs where each country pledges what is possible in its capacity. Concerns around justice are central to the debates about mitigation, adaptation and climate governance as they open up opportunities to discuss who cuts emissions, who pays for the pollution, whose knowledge counts and who has the capability to respond to the problem (Schroeder et al. 2012).

Shue (2014) points for justice considerations to be an integral part of humanity's efforts to mitigate and adapt to climate change, at the global as well as sub-national levels. Equity and fairness are important elements of the justice framing in climate change research, and relate to both procedural justice (i.e. participation in decision making) and distributive justice (i.e. how costs and benefits of climate actions are distributed). This framing recognizes that climate change presents significant threats to future wellbeing in that future generations are likely to be vulnerable to climate impacts and are least represented in current decisions that shape future outcomes.

Further, environmental ethics argues that ecosystems have a right to exist in natural state; intergenerational equity says we should leave natural state as much as possible for future generations.

1.4.7 Multidimensional costs and benefits

The costs and benefits of a 1.5 °C world will be multidimensional and will occur at a variety of spatial and temporal contexts. Actions and strategies will be translated from local to global scales and originate from international agreements that could be interpreted at the local level. Policies implemented at the local level enable the condition to allow for an increase of the ambition of response and transformative action. Examples include application of technology innovation aspects (funding, governance), air pollution control policies, and low carbon economy initiatives.

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

The section examines the transferability of assessment and methodologies for evaluating 1.5 °C conditions and pathways. Assessment frameworks and emerging methodologies that integrate mitigation and adaptation with sustainable development and enable the evaluation of outcomes are an important component of understanding the implication of a 1.5 °C world. The literature of 1.5 °C is rapidly developing and broadly used in the report. The understanding of 1.5 °C is expanded through use of model-based, empirically-based and expert judgment-based approaches to "downscale" existing literature for 1.5 °C assessment.

1.5.1 Building on AR5 and SREX

The assessment approaches or methodologies and tools used in AR5 and SREX for impacts and mitigation pathways included large-scale computer models, referred to as Integrated Models (IM) or its subset, the Integrated Assessment Models (IAM); Coupled Model Intercomparison Project (CMIP); Shared Socioeconomic Pathways (SSP); case studies and regional analyses. Building on these tools, this report provides new information on assessing 1.5 °C for climate change impacts and mitigation especially the information about emissions pathways, energy and land-use transitions, and aggregate economic costs of mitigation.

A new generation of 1.5 °C scenarios from Integrated Assessment Models (IAMs) were developed and concluded that to meet the long term goal of 1.5 °C in the Paris Agreement, net emissions would need to reach zero by 2050, and then go below zero in the second half of the century (2100) (see Advance Project, http://www.fp7-advance.eu/). Due to the scale of the challenge for achieving 1.5°C, 80% of global integrated assessment models use Negative Emissions Technologies (NETs) in their simulations (Hampton 2016). Integrated energy–economy–environment scenarios that keep warming to below 1.5 °C by 2100 show a faster scale-up of mitigation action in most sectors and the move from a 2 °C- to a 1.5 °C-consistent world will be achieved mainly through additional reductions of CO_2 (Rogelj et al. 2016).

Mitchell et al. (2016) pointed out that many experiments, for example, the CMIP, are not specifically designed to run simulations and projections for informing the 1.5 °C world and thus the design of the half a degree additional warming, projections, prognosis and impacts (HAPPI) experiment. The HAPPI provides a framework for the generation of climate data describing how the climate, and in particular extreme weather, might differ from the present day in worlds that are 1.5 and 2.0 °C warmer than pre-industrial conditions (Déqué et al. 2016). The SSPs are also part of the new scenario framework that combines the Representative Concentration Pathways (RCPs) in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development (Riahi et al. 2015).

1.5.2 Types of knowledge and evidence used in the report

Within this framing, the report provides an assessment of four levels of knowledge sources: 1. State of knowledge of changes in the physical climate system, and associated impacts and vulnerabilities with emphasis on new information since the publication of the IPCC's Fifth Assessment Report (AR5) and the cutoff date April 2018; 2. Grey literature such as reports from government and industry; 3. Social science literature knowledge; 4. Mitigation pathways based on projections in the future; and, 5. Co-production local knowledge.

An appropriate knowledge base plus new and adaptable institutional structure at different scales will be required to create, for example, the required policy and legal frameworks and establish resources for implementing various response options to the 1.5 °C warming. Incorporating knowledge from different sources and setting a multi-faceted information channel, educating and building awareness at various levels will advance decision making and implementation of context specific response to 1.5 °C warming and associated uncertainties (AR5 Chapter 15, 2014).

[START BOX 1.2 HERE]

Box 1.2: Experiencing 1.5 °C - Opportunities and challenges of visualizing a 1.5 °C world using observations of climate impacts today; climate change and variability to date; extreme weather and the potential role of community knowledge

Literature or information about regional climate change impacts is limited and there are research gaps on the rate of change and regional dimensions on the impacts of 1.5 °C. Traditional knowledge and experience offers valuable insights, and can complement scientific data with chronological and landscape-specific precision and detail that is critical for verifying climate models and evaluating climate change scenarios (Raygorodetsky 2011). Fernández-Llamazares et al. (2015) defines Traditional Ecological knowledge (TEK) as "knowledge obtained from observation, experiences, oral history and accumulation." Western climate data tends to be limited or absent from places like Central Africa, Central America and the Himalayas but there are people with relevant data and information. Savo et al. (2016) gathered observations covering 137 countries involving more than 90,000 people whose traditional ways of life rely on nature and where weather stations are absent to fill a knowledge gap in climate change science, which is dominated by data and computer models. They found some 70 percent of those interviewed had witnessed changes in seasons, rainfall patterns and temperature. The observations generally align with data and models developed to predict changes in the climate. McMillen et al. (2014) reported that in some regions like Oceania, indigenous people used climate observations to develop customary calendars that include expectations of weather (e.g., wet and dry seasons) in phonological characteristics of fruiting of breadfruit (Artocarpus altilis), or the rising and spawning of the palolo sea worm (Eunice viridis).

[INSERT FIGURE BOX1.2 FIGURE 1 HERE]

Box 1.2, Figure 1: Realized experience of present-day warming. Colors indicate human-induced warming in 2016 (relative to 1861-1880) for the most strongly warming month at any location. The density of dots indicates the population (2015) in any 1°x1° grid box. Warming trends are calculated in an identical way to Figure 1.2. Hatched areas indicate regions where over 50% of the temperature record is missing and warming trends are not calculated.

[INSERT FIGURE BOX1.2 FIGURE 2 HERE]

Box 1.2, Figure 2: Probability density function for the data shown in Figure 1 of this box. Approximately 80% of the global population that live in regions for which local warming trends can be calculated have already experienced over 1.5 °C of warming in at least 1 month of the year.

The value of traditional knowledge related to climate is being more widely considered as critical to understanding the climate change impacts at regional and local level and in developing local climate change adaptation plans and strategies that sustain resilience of social-ecological systems at the interconnected local, regional and global scales (Nakashima et al. 2012). In their review of 10,660 observations from 2,230 localities in 137 countries, Savo et al. (2016) reported extensive impacts of climatic changes on both wild and domesticated plants and animals and threaten the food security of local communities. Their finding suggested that climate change is disrupting community's livelihoods and that local observations can make an important contribution to understanding climate change impacts on ecosystems and societies and adaptation options. For example, they reported that the Sweden's Sami herders, were abandoning traditional ways due to changes in ice formation and weather, whilst in Bangladesh, an upsurge of strong winds and storms was forcing some fishermen to moor their boats rather than set out to sea.

While traditional knowledge is being more widely considered as critical to developing local climate change adaptation plans and strategies, it either exists in grey literature outside of peer-reviewed process, or remains in oral form and in most cases falls outside the scope scientific literature on climate change impacts and mitigation (Leon et al. 2015).

[END BOX 1.2 HERE]

1.5.3 Assessment across space and timescales (Assessment and methodologies across space and timescales)

Information for the report is global in scope and includes regional analysis. The report provides synthesis of municipal, sub national, and national case studies. The time scale of the assessment is the 21st century.

1.5.4 System-level framing: Anthropocene, transition theory, transformative change

The assessment of the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty requires a holistic approach that integrates across time and geographical scales of the related socio-economic and biophysical issues. This assessment is therefore amenable to the concept of the Anthropocene, emerging to be considered as a new geological era, serving to convey the unprecedented human-role in the observed changes on the biophysical systems such as impacts of climate extremes, ocean acidification, species extinction and sea level rise that have wide implications on the socio-cultural and economic systems. The Anthropocene helps in understanding the culmination of past and present human-environmental relations across scale providing for an opportunity to better visualize the future and minimizing pitfalls.

Despite the diverse and sometimes controversial views on the interpretation of the Anthropocene concept, emerging literature point to its relevance to climate change. This is because human-driven climate change expresses the depth of the global interlinkages within the human and nature entanglement that are an embodiment of the Anthropocene concept. Further, the factor that humans have the capability to change the environment on geological scales justifies human capability to establish solutions at a global level to the climate change challenge (Harrington 2015). For example, a search for a global response to climate change entails identifying ways of motivating shifts or transformations within the human-nature interactions that could reduce the threat of climate change, enhance sustainable development and limit global inequalities. One of the questions to be addressed by this assessment is how, under the Anthropocene, can mitigation and adaptation be better integrated with sustainable development to minimize negative environmental impacts and reduce poverty?

1.5.5 Transformation, Transformation Pathways, and Transition

This report assesses how the global society can transform to meet the condition of a 1.5 °C world. The IPCC in AR5 defines transformation as a change in the fundamental attributes of natural and human systems. The AR5 also defines a transformation pathway as the trajectory taken over time to meet different goals for GHG emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up and in the pace and direction of technological change. Within the report transformation pathways are defined in baseline and reference, levels, emission scenarios, mitigation scenarios, RCPs and SSPs. The process of transformation includes system level transitions from one regime to another. These transitions can be gradual or abrupt. The report assesses the different physical and societal contexts for transitions.

1.5.6 Building social, institutional and knowledge capital

Multiple types of knowledge, meanings and beliefs, different actors and institutions attach to climate threats, risks and responses, and how these different knowledge interact when building awareness and capacities are important for meeting the challenge posed by a 1.5 °C target. The report assessment incorporates local observational community knowledge and policy/institutional knowledge. Requirements for educating and building awareness include emerging cultural norms and behaviour associated with discourses, narratives of a 1.5 °C world. The report also assesses how these discourses are expected to change and how will they be impacted and communicated. Climate risk communication strategies are central to equipping policy debates and the decision-making process.

1.6 Consideration and communication of confidence, uncertainty and risk

Careful consideration and clear communication of levels of confidence and uncertainty is fundamental to the work of the IPCC. This Special Report relies on the IPCC's uncertainty guidance provided in Mastrandrea et al. (2011), building on IPCC (2005), Manning et al. (2004) and Moss and Schneider (2000), that was the basis for the consistent treatment of uncertainty in AR5. Some simplifications and clarifications are proposed to address the specific circumstances of this Report. The AR5 relied on two metrics for communicating the degree of certainty in key findings:

- Qualitative expressions of confidence in the validity of a finding based on the amount of and level of agreement in the evidence available; and
- Quantitative expressions of likelihood or probability of specific events or outcomes.

In both cases, specific terms were adopted to ensure consistency of language across chapters and working groups, but differences of practice emerged, with greater use of confidence expressions by Working Groups 2 and 3, and likelihood by Working Group 1. This is a cross-working-group report with a need for consistent practice spanning physical climate; impacts, vulnerabilities and risks; and mitigation options. For reasons given below, the authors of this Special Report express their key findings using qualitative expressions of confidence and numerical ranges where possible. Following the practice in AR5 Working Groups 2 and 3, and in contrast to Working Group 1, the use of probabilistic ("likely" etc.) qualifiers is generally avoided in Executive Summaries and the Summary for Policymakers. Where findings explicitly concern probabilities, or frequency of occurrence within an ensemble, these are given numerically or using phrases such as "even chance" or "two in three chance" to avoid any ambiguity.

1.6.1 Background – confidence scale:

Five qualifiers are used to express levels of confidence in key findings, ranging from "very low", through "low", "medium", "high", to "very high". The assessment of confidence involves at least two dimensions (see Figure 1.8), one being the type, quality, amount or internal consistency of individual lines of evidence, the second being the level of agreement between different lines of evidence. Very high confidence findings must either be supported by a high level of agreement across multiple lines of mutually independent and individually robust lines of evidence or, if only a single line of evidence is available, by a very high level of understanding of the processes underlying that evidence. High confidence implies either high agreement across different lines of evidence that may be individually less robust, or lower agreement but greater individual robustness. There are multiple ways of supporting a "medium confidence" qualifier, and further explanation may be required to elaborate whether the issue is lack of agreement between, or the robustness of, different lines of evidence. Findings of low or very low confidence are presented only if they address a topic of major concern.

1.6.2 Background – likelihood scale:

The IPCC uses a calibrated language scale to communicate assessed probabilities of outcomes, ranging from exceptionally unlikely (<1%), extremely unlikely (<5%), very unlikely (<10%), unlikely (<33%), about as likely as not (33-66%), likely (>66%), very likely (>90%), extremely likely (>95%) and virtually certain (>99%). These terms are normally only applied to assessed probabilities supported by several, or one very well understood, robust lines of evidence (hence findings associated with high or very high confidence). Where findings are based on frequencies within model ensembles, calibrated uncertainty language is not used to communicate those frequencies unless these are assessed (with other lines of evidence) to correspond to probabilities in the real world. Figures and text in AR5 normally use 5-95% confidence intervals for observable quantities and the 5-95% frequency interval for ranges of model ensembles. These may be interpreted as "very likely" intervals in the first case, but not in the second unless supported by additional lines of evidence.

1.6.3 Challenges in the context of this Special Report:

Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the timetable on which this report is being compiled and the current state of the academic literature on 1.5 °C mean that findings based on multiple lines of robust evidence for which quantitative probabilistic results can be expressed may be very few, and those that can be made may not be the most policy-relevant. This introduces a communication challenge: in AR5, whenever a likelihood assessment was given, it could be assumed that it was associated with high or very high confidence, and hence this was not stated. When findings are presented at various levels of confidence, it may not always be clear to the reader that those that omit a confidence qualifier are implicitly high or very high confidence (or, worse, that the "high confidence" qualifier comes to be used only to distinguish statements that are not "very high confidence"). While stressing that this does not entail a revision to the well-established uncertainty guidance, in this Special Report an effort is made to avoid relying on implicit confidence qualifiers: if a qualifier is intended, then it is stated explicitly. Double-qualified expressions that combine both likelihood and confidence language can, however, easily become impenetrable (e.g. "very likely (medium confidence)"): hence, where possible, key findings are expressed in this report using confidence qualifiers alone with numerical expressions of frequency or probability as appropriate.

Second, many of the most important findings of this Special Report are highly conditional precisely because they refer to ambitious mitigation scenarios. This also presents challenges in communication with probabilistic language. The risks associated with 4 °C of warming may not be very different from the risks associated with a scenario that is expected to result in 4°C of warming, but which might result in 3 °C or 5 °C depending on the global climate response. This is not true of ambitious mitigation scenarios: the range of risks associated with 1.5 °C of global temperature increase may be very different from the risks associated with a scenario that has an even chance of meeting the 1.5 °C goal. In the first case, risks are conditioned on the global temperature goal actually being met, while in the second, they also need to allow for a substantial chance of warming exceeding 2 °C because of uncertainty in the global temperature response. Such conditional probabilities often depend strongly on how conditions are specified, such as how temperature goals are met, whether through early emission reductions, greater reliance on negative emissions following an overshoot, or later reductions coupled with a low climate response. Hence whether a certain risk is deemed "likely" or "very likely" at 1.5 °C may depend strongly on how 1.5 °C is specified, whereas a statement that a certain risk may be substantially higher at 2 °C relative to 1.5 °C may be much more robust. Again, this cautions against the use of probabilistic language to convey highly conditional probabilities in situations where the precise specification of the conditions may not be transparent.

Third, the traditional application of probabilistic language in IPCC applies to relatively passive systems, such as the projected response of the climate system to a specific emissions scenario. Achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly for specific outcomes and incorporating new information as it becomes available. The focus of uncertainty shifts from the climate outcome itself to the level of mitigation effort that may be required to achieve it. The interpretation of probabilistic statements about future actions, which may in turn be informed by these statements, is clearly a challenge. It may also be unnecessary: in the context of robust decision-making, many near-term policies that are needed to keep open the option of achieving 1.5 °C are the same, regardless of the actual probability that the goal will be met.

In the light of these challenges, it is proposed to present summary findings in this report as far as possible using confidence language, using numerical ranges and probabilities where appropriate, avoiding the use of double-qualified statements.

[INSERT FIGURE 1.8 HERE]

Figure 1.8: The two dimensions of evidence and agreement together determine the level of confidence in a key finding, adapted from Mastrandrea et al. (2011). This figure illustrates how, while there are relatively few ways of supporting a "very high confidence" or "very low confidence" statement, there are multiple ways of supporting a "medium confidence" statement. Note: this figure could be turned on its corner, so the grid is diagonal and the isolines of shading/confidence are horizontal.

1.7 Storyline of the report

This report is formed by 5 chapters in addition to the summary for policy makers. The report has a series of boxes to elucidate specific or cross-cutting themes and in addition each chapter has a section on frequently asked questions. This Chapter 1, on Framing and context and is followed by Chapter 2 that is focused on Mitigation pathways compatible with 1.5 °C in the context of sustainable development. Impacts of 1.5 °C global warming on natural and human systems are then covered in Chapter 3 of the report. Chapter 4 is about Strengthening and implementing the global response to the threat of climate change. While the final Chapter, 5, covers sustainable development, poverty eradication and reducing inequalities in the context of 1.5 °C global warming.

References

Agard, J., and E. L. Schipper, 2014: Annex II: Glossary. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1757–1776.

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen, 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163–1166, doi:10.1038/nature08019.

Allen, M. R., J. S. Fuglestvedt, K. P. Shine, A. Reisinger, R. T. Pierrehumbert, and P. M. Forster, 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Chang.*, **6**, 1–5, doi:10.1038/nclimate2998.

Andrys, J., J. Kala, and T. J. Lyons, 2016: Regional climate projections of mean and extreme climate for the southwest of Western Australia (1970-1999 compared to 2030-2059). *Climate Dynamics*.

Archer, D., and V. Brovkin, 2008: The millennial atmospheric lifetime of anthropogenic CO2. *Clim. Change*, **90**, 283–297, doi:10.1007/s10584-008-9413-1.

Bindoff, N. L., and Coauthors, 2013: Detection and Attribution of Climate Change: from Global to Regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 426–488.

Birkmann, J., T. Welle, W. Solecki, S. Lwasa, and M. Garschagen, 2016: Boost resilience of small and mid-sized cities. *Nature*, **537**, 605–608, doi:10.1038/537605a. http://www.nature.com/doifinder/10.1038/537605a (Accessed April 7, 2017).

Boucher, O., and G. A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmos. Environ.*, **44**, 3343–3345, doi:10.1016/j.atmosenv.2010.04.032. http://linkinghub.elsevier.com/retrieve/pii/S1352231010003262 (Accessed April 7, 2017).

Brinkman, T. J., W. D. Hansen, F. S. Chapin, G. Kofinas, S. BurnSilver, and T. S. Rupp, 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Clim. Change*, **139**, 413–427, doi:10.1007/s10584-016-1819-6. http://link.springer.com/10.1007/s10584-016-1819-6 (Accessed April 8, 2017).

Busby, J., 2016: After Paris: Good enough climate governance. *Curr. Hist.*, **15**, 3–9. http://www.currenthistory.com/Busby_CurrentHistory.pdf (Accessed April 7, 2017).

Campbell, B. M., and Coauthors, 2016: Reducing risks to food security from climate change. *Glob. Food Sec.*, 0–1, doi:10.1016/j.gfs.2016.06.002. http://linkinghub.elsevier.com/retrieve/pii/S2211912415300262.

Cowtan, K., and Coauthors, 2015: Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophys. Res. Lett.*, **42**, 6526–6534, doi:10.1002/2015GL064888. http://doi.wiley.com/10.1002/2015GL064888 (Accessed April 6, 2017).

Daniel, J. S., S. Solomon, T. J. Sanford, M. McFarland, J. S. Fuglestvedt, and P. Friedlingstein, 2012: Limitations of single-basket trading: lessons from the Montreal Protocol for climate policy. *Clim. Change*, **111**, 241–248, doi:10.1007/s10584-011-0136-3. http://link.springer.com/10.1007/s10584-011-0136-3 (Accessed April 7, 2017).

Davis, S. J., K. Caldeira, and H. D. Matthews, 2010: Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science (80-.).*, **329**, 1330–1333, doi:10.1126/science.1188566.

Davis, S. J., and R. H. Socolow, 2014: Commitment accounting of CO2 emissions. *Environ. Res. Lett.*, **9**, 84018, doi:10.1088/1748-9326/9/8/084018. http://stacks.iop.org/1748-9326/9/i=8/a=084018.

Denton, F., and Coauthors, 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1101–1131.

Déqué, M., S. Calmanti, O. B. Christensen, A. Dell Aquila, C. F. Maule, A. Haensler, G. Nikulin, and C. Teichmann, 2016: A multi-model climate response over tropical Africa at +2°C. *Climate Services*.

Deser, C., R. Knutti, S. Solomon, and A. S. Phillips, 2012: Communication of the Role of Natural Variability in Future North American Climate. *Nat. Clim. Chang.*, **2**, 775–779, doi:10.1038/nclimate1562.

Dietz, T., G. Gardner, J. Gilligan, P. Stern, and M. Vandenbergh, 2009: Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proc. Natl. Acad. Sci.*, **106**, 18452–18456.

Diffenbaugh, N. S., and A. Charland, 2016: Probability of emergence of novel temperature regimes at different levels of cumulative carbon emissions. *Front. Ecol. Environ.*, **14**, 418–423, doi:10.1002/fee.1320.

E., S., and Coauthors, 2015: National and Sub-national Policies and Institutions. *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report*, Intergovernmental Panel on Climate Change, Ed., Cambridge University Press, Cambridge, 1141–1206 https://www.cambridge.org/core/books/climate-change-2014-mitigation-of-climate-change/national-and-subnational-policies-and-institutions/1659CB70CCA80B6E15330AF5F6C165C8.

Ebi, K. L., and G. Yohe, 2013: Adaptation in first- and second-best worlds. *Curr. Opin. Environ. Sustain.*, **5**, 373–377, doi:10.1016/j.cosust.2013.06.004. http://www.sciencedirect.com/science/article/pii/S1877343513000730 (Accessed March 29, 2017).

Eby, M., K. Zickfeld, A. Montenegro, D. Archer, K. J. Meissner, and A. J. Weaver, 2009: Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations. *J. Clim.*, **22**, 2501–2511, doi:10.1175/2008JCLI2554.1.

Eby, M., A. J. Weaver, K. Alexander, K. Zickfeld, A. Abe-Ouchi, A. A. Cimatoribus, and E. Crespin, 2013: Geoscientific Instrumentation Methods and Data Systems Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity. *Clim. Past*, **9**, 1111–1140, doi:10.5194/cp-9-1111-2013.

Edenhofer, O., and J. Minx, 2014: Mapmakers and navigators, facts and values. *Science (80-.).*, **345**, 37–38, doi:10.1126/science.1255998. http://www.sciencemag.org/cgi/doi/10.1126/science.1255998 (Accessed December 12, 2015).

Edenhofer, O., and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environ. Sci. Policy*, **51**, 56–64, doi:10.1016/j.envsci.2015.03.017. http://www.sciencedirect.com/science/article/pii/S1462901115000660 (Accessed September 11, 2015).

Edenhofer, O., and Coauthors, 2014: Technical Summary. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 33–107.

Edwards, M. R., and J. E. Trancik, 2014: Climate impacts of energy technologies depend on emissions timing. *Nat. Clim. Chang.*, **4**, 347–352, doi:10.1038/nclimate2204. http://www.nature.com/nclimate/journal/v4/n5/full/nclimate2204.html (Accessed June 13, 2016).

Eliseev, A. V., 2012: Climate change mitigation via sulfate injection to the stratosphere: impact on the global carbon cycle and terrestrial biosphere. *Atmos. Ocean. Opt.*, **25**, 405–413, doi:10.1134/S1024856012060024.

Eom, J., J. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and D. P. Van Vuuren, 2015: The impact of near-term climate policy choices on technology and emission transition pathways. *Technol. Forecast. Soc. Change*, **90**, 73–88, doi:10.1016/j.techfore.2013.09.017. http://dx.doi.org/10.1016/j.techfore.2013.09.017.

Etminan, M., G. Myhre, E. J. Highwood, and K. P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.*, **43**, 12,614-12,623, doi:10.1002/2016GL071930. http://doi.wiley.com/10.1002/2016GL071930 (Accessed April 5, 2017).

Faber, J., and Coauthors, 2012: *Behavioural climate change mitigation options and their appropriate inclusion in quantitative longer term policy scenarios*. CE Delft, Fraunhofer ISI, LEI Wageningen, Delft,.

FAO, IFAD, and WFP., 2015: *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress.* 1-54 pp. http://www.fao.org/3/a4ef2d16-70a7-460a-a9ac-2a65a533269a/i4646e.pdf.

Fawcett, A. A., and Coauthors, 2015: Can Paris pledges avert severe climate change? *Science (80-.).*, **350**, 1168–1169, doi:10.1126/science.aad5761. http://www.sciencemag.org/content/350/6265/1168 (Accessed December 4, 2015).

Fernández-Llamazares, Á., I. Díaz-Reviriego, A. C. Luz, M. Cabeza, A. Pyhälä, and V. Reyes-García, 2015: Rapid ecosystem change challenges the adaptive capacity of Local Environmental Knowledge. *Glob. Environ. Change*, **31**, 272–284, doi:10.1016/j.gloenvcha.2015.02.001. http://www.sciencedirect.com/science/article/pii/S0959378015000187.

Fischedick, M., and Coauthors, 2014: Industry. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 739–810.

Flato, G., and Coauthors, 2013: Evaluation of Climate Models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 741–866.

Fleurbaey, M., and Coauthors, 2014: Sustainable Development and Equity. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Fricko, O., and Coauthors, 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.*, **42**, 251–267, doi:10.1016/j.gloenvcha.2016.06.004. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004.

Fricko, O., S. C. Parkinson, N. Johnson, M. Strubegger, M. T. van Vliet, and K. Riahi, 2016: Energy sector water use implications of a 2 °C climate policy. *Environ. Res. Lett.*, **11**, 34011, doi:10.1088/1748-9326/11/3/034011.

Friedlingstein, P., and Coauthors, 2014: Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nat. Geosci.*, **7**, 709–715, doi:10.1038/ngeo2248. http://www.nature.com/doifinder/10.1038/ngeo2248 (Accessed April 4, 2017).

Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti, 2013: Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks. *J. Clim.*, **27**, 511–526, doi:10.1175/JCLI-D-12-00579.1.

Frölicher, T. L., 2016: Climate response: Strong warming at high emissions. *Nat. Clim. Chang.*, **6**, 823–824, doi:10.1038/nclimate3053.

Frölicher, T. L., and D. J. Paynter, 2015: Is the climate response to carbon emissions path dependent? *Geophys. Res. Lett.*, **39**, L05703, doi:10.1088/1748-9326/10/7/075002. http://iopscience.iop.org/article/10.1088/1748-9326/10/7/075002 (Accessed April 4, 2017).

Fujimori, S., 2016: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, This Special Issue, doi:10.1016/j.gloenvcha.2016.06.009. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009.

Fujimori, S., X. Su, J.-Y. Liu, T. Hasegawa, K. Takahashi, T. Masui, and M. Takimi, 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *Springerplus*, **5**, 1620, doi:10.1186/s40064-016-3235-9. http://www.ncbi.nlm.nih.gov/pubmed/27652193 (Accessed April 6, 2017).

Fuss, S., and Coauthors, 2014: Betting on negative emissions. *Nat. Clim. Chang.*, **4**, 850–853, doi:10.1038/nclimate2392. http://www.nature.com/nclimate/journal/v4/n10/full/nclimate2392.html (Accessed June 15, 2015).

Gasser, T., C. Guivarch, K. Tachiiri, C. D. Jones, and P. Ciais, 2015: Negative emissions physically needed to keep global warming below 2 °C. *Nat. Commun.*, **6**, 7958, doi:10.1038/ncomms8958. http://www.nature.com/ncomms/2015/150803/ncomms8958/full/ncomms8958.html.

Geels, F. W., F. Berkhout, and D. P. van Vuuren, 2016: Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Chang.*, **6**, 576–583, doi:10.1038/nclimate2980. http://dx.doi.org/10.1038/nclimate2980.

Geoffroy, O., D. Saint-Martin, and A. Voldoire, 2015: Land-sea warming contrast: the role of the horizontal energy transport. *Clim. Dyn.*, **45**, 3493–3511, doi:10.1007/s00382-015-2552-y.

Gernaat, D. E. H. J., K. Calvin, P. L. Lucas, G. Luderer, S. A. C. Otto, S. Rao, J. Strefler, and D. P. van Vuuren, 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Glob. Environ. Chang.*, **33**, 142–153, doi:10.1016/j.gloenvcha.2015.04.010. http://dx.doi.org/10.1016/j.gloenvcha.2015.04.010.

Gillett, N. P., V. K. Arora, D. Matthews, and M. R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. *J. Clim.*, **26**, 6844–6858, doi:10.1175/JCLI-D-12-00476.s1.

Gillett, N. P., and H. D. Matthews, 2010: Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. *Environ. Res. Lett.*, **5**, 34011, doi:10.1088/1748-9326/5/3/034011.

Goode, W. J., 1997: Rational choice theory. *Am. Sociol.*, **28**, 22–41.

Goodwin, P., R. G. Williams, and A. Ridgwell, 2014: Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake. *Nat. Geosci.*, **8**, 29–34, doi:10.1038/ngeo2304.

Gregory, J. M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophys. Res. Lett.*, **43**, 3911–3920, doi:10.1002/2016GL068406. http://doi.wiley.com/10.1002/2016GL068406 (Accessed April 5, 2017).

Griggs, D., and Coauthors, 2014: An integrated framework for sustainable development goals. *Ecol. Soc.*, **19**, doi:10.5751/ES-07082-190449.

Gupta, S., and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Inter- Gov. Panel Clim. Chang.*, 1207–1246, doi:10.1017/CBO9781107415416.022.

Hallegatte, S., and Coauthors, 2016: Mapping the climate change challenge. *Nat. Clim. Chang.*, **6**, 663–668, doi:10.1038/nclimate3057. http://dx.doi.org/10.1038/nclimate3057%5Cnhttp://www.nature.com/doifinder/10.1038/nclimate3057.

Hampton, S., 2016: What technologies are available for meeting the 1.5C goal? *Carbon Br.*,. http://www.carbonbrief.org/what-technologies-are-available-for-meeting-1-point-5-degrees (Accessed April 7, 2017).

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global Surface Temperature Change. *Rev. Geophys.*, **48**, RG4004, doi:10.1029/2010RG000345. http://doi.wiley.com/10.1029/2010RG000345 (Accessed April 6, 2017).

Harrington, C., 2015: The Ends of the World: International Relations and the Anthropocene. *2015 Millenn. Conf. Fail. Denial World Polit.*, 1, doi:10.1177/0305829816638745.

Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr, and J. Scheffran, 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.*, **51**, 113–149, doi:10.1002/rog.20004. http://onlinelibrary.wiley.com/doi/10.1002/rog.20004/abstract (Accessed January 6, 2014).

Hauck, J., P. Köhler, D. Wolf-Gladrow, and C. Völker, 2016: Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO2 removal experiment. *Environ. Res. Lett.*, **11**, 24007–24011, doi:10.1088/1748-9326/11/2/024007.

Heck, V., J. F. Donges, and W. Lucht, 2016: Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal. *Earth Syst. Dyn.*, **7**, 783–796, doi:10.5194/esd-7-783-2016.

Heck, V., D. Gerten, W. Lucht, and L. R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a “green” form of geoengineering? A global modelling study. *Glob. Planet. Change*, **137**, 123–130, doi:10.1016/j.gloplacha.2015.12.008.

Hermoso, V., 2017: Freshwater ecosystems could become the biggest losers of the Paris Agreement. *Glob. Chang. Biol.*, doi:10.1111/gcb.13655. http://doi.wiley.com/10.1111/gcb.13655.

Hermwille, L., W. Obergassel, H. E. Ott, and C. Beuermann, 2015: UNFCCC before and after Paris – what's necessary for an effective climate regime? *Clim. Policy*, **3062**, 1–21, doi:10.1080/14693062.2015.1115231. http://dx.doi.org/10.1080/14693062.2015.1115231.

Hof, A. F., M. G. J. den Elzen, A. Admiraal, M. Roelfsema, D. E. H. J. Gernaat, and D. P. van Vuuren, 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. *Environ. Sci. Policy*, **71**, 30–40, doi:10.1016/j.envsci.2017.02.008. http://www.sciencedirect.com/science/article/pii/S1462901116308978 (Accessed April 6, 2017).

Humpenöder, F., and Coauthors, 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.*, **9**, 64029, doi:10.1088/1748-9326/9/6/064029. http://iopscience.iop.org/1748-9326/9/6/064029 (Accessed June 24, 2014).

Huntingford, C., and J. Lowe, 2007: Overshoot scenarios and climate change. *Science (80-.).*, **316**, 829, doi:10.1126/science.316.5826.829b.

Huntingford, C., J. A. Lowe, L. K. Gohar, N. H. A. Bowerman, M. R. Allen, S. C. B. Raper, and S. M. Smith, 2012: The link between a global 2 °C warming threshold and emissions in years 2020, 2050 and beyond. *Environ. Res. Lett.*, **7**, 14039, doi:10.1088/1748-9326/7/1/014039.

IEA, 2016: *World Energy Investment 2016*. IEA/OECD, Paris,.

Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO2 and ocean acidification. *Geophys. Res. Lett.*, **40**, 5909–5914, doi:10.1002/2013GL057981.

IPCC, 2014: Summary for Policymakers - Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambirdge University Press, Cambridge, UK, and New York, NY, USA, 1–30.

IPCC, 2014: Summary for Policymakers. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability - Contrib. Work. Gr. II to Fifth Assess. Rep.*, 1–32, doi:10.1016/j.renene.2009.11.012.

IPCC, 2013: Summary for Policymakers. *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 33, doi:10.1017/CBO9781107415324.

IPCC, 2012: Summary for Policymakers. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, 1–20 papers2://publication/uuid/41AD43FB-2529-4ACD-AD33-4C2D0AB4A0F3.

IPCC, 2005: *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties*. http://www.ipcc-wg2.awi.de/guidancepaper/uncertainty-guidance-note.pdf (Accessed April 5, 2017).

IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 151 pp.

IPCC, 2014: Climate Change 2014 Synthesis Report Summary - Chapter for Policymakers. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 31.

Iyer, G. C., L. E. Clarke, J. A. Edmonds, B. P. Flannery, N. E. Hultman, H. C. McJeon, and D. G. Victor, 2015: Improved representation of investment decisions in assessments of CO2 mitigation. *Nat. Clim. Chang.*, **5**, 436–440, doi:10.1038/nclimate2553. http://www.nature.com/nclimate/journal/v5/n5/full/nclimate2553.html (Accessed April 23, 2015).

Iyer, G. C., and Coauthors, 2015: The contribution of Paris to limit global warming to 2 °C. *Environ. Res. Lett.*, **10**, 125002, doi:10.1088/1748-9326/10/12/125002. http://stacks.iop.org/1748-9326/10/i=12/a=125002.

Jackson, R. B., and Coauthors, 2008: Protecting climate with forests. *Environ. Res. Lett.*, **3**, 44006, doi:10.1088/1748-9326/3/4/044006.

Jakob, M., and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.*, **11**, 104010, doi:10.1088/1748-9326/11/10/104010. http://stacks.iop.org/1748-9326/11/i=10/a=104010?key=crossref.4cd77602bc9540b790e45408383c5286 (Accessed April 5, 2017).

Jewell, J., and Coauthors, 2016: Comparison and interactions between the long-term pursuit of energy independence and climate policies. *Nat. Energy*, **1**, 16073, doi:10.1038/nenergy.2016.73. http://www.nature.com/articles/nenergy201673 (Accessed June 8, 2016).

Jiang, L., and B. C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 193–199, doi:10.1016/j.gloenvcha.2015.03.008. http://www.sciencedirect.com/science/article/pii/S0959378015000394 (Accessed April 4, 2017).

Johannessen, S. C., and R. W. Macdonald, 2016: Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.*, **11**, 113001, doi:10.1088/1748-9326/11/11/113001.

Johnson, N., V. Krey, D. L. McCollum, S. Rao, K. Riahi, and J. Rogelj, 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change*, **90**, 89–102, doi:10.1016/j.techfore.2014.02.028. http://www.sciencedirect.com/science/article/pii/S0040162514000924 (Accessed April 5, 2017).

Jones, C. D., and Coauthors, 2016: Simulating the Earth system response to negative emissions. *Environ. Res. Lett.*, **11**, 95012, doi:10.1088/1748-9326/11/9/095012.

Jones, C., and Coauthors, 2013: Twenty-First-Century Compatible CO 2Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. *J. Clim.*, **26**, 4398–4413, doi:10.1175/JCLI-D-12-00554.1.

Jones, G. S., S. F. B. Tett, and P. A. Stott, 2003: Causes of atmospheric temperature change 1960-2000: A combined attribution analysis. *Geophys. Res. Lett.*, **30**, n/a-n/a, doi:10.1029/2002GL016377. http://doi.wiley.com/10.1029/2002GL016377 (Accessed April 6, 2017).

Joos, F., and Coauthors, 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos. Chem. Phys.*, **13**, 2793–2825, doi:10.5194/acp-13-2793-2013.

Joseph, R., 2016: The Anthropocene and Climate Crisis. University of Alberta, https://era.library.ualberta.ca/files/ch128nd93d#.WNbXAWclG70.

Kabir, M. I., M. B. Rahman, W. Smith, M. A. F. Lusha, S. Azim, and A. H. Milton, 2016: Knowledge and perception about climate change and human health: findings from a baseline survey among vulnerable communities in Bangladesh. *BMC Public Health*, **16**, 266, doi:10.1186/s12889-016-2930-3. http://www.ncbi.nlm.nih.gov/pubmed/26979241 (Accessed April 8, 2017).

Karen C., S., and Coauthors, 2014: Human Settlements, Infrastructure, and Spatial Planning. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 923–1000.

KC, S., and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004. http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Keith, D. W., M. Ha-Duong, and J. K. Stolaroff, 2006: Climate Strategy with CO2 Capture from the Air. *Clim. Change*, **74**, 17–45, doi:10.1007/s10584-005-9026-x. http://link.springer.com/10.1007/s10584-005-9026-x (Accessed April 16, 2015).

Keith, D. W., and J. S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Clim. Change*, **54**, 375–377. http://dx.doi.org/10.1023/A:1016187420442.

Kheshgi, H. S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20**, 915–922, doi:10.1016/0360-5442(95)00035-F. http://linkinghub.elsevier.com/retrieve/pii/036054429500035F (Accessed April 1, 2017).

Kirtman, B., A. Adedoyin, and N. Bindoff, 2013: Near-term Climate Change: Projections and Predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 953–1028 ftp://halo.ess.uci.edu/Public/prather/paper_N2O/IPCC WGI AR5 Ch 11 v30.doc.

Klein, D., and Coauthors, 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Clim. Change*, **123**, 705–718, doi:10.1007/s10584-013-0940-z.

Knutti, R., J. Rogelj, J. Sedláček, and E. M. Fischer, 2015: A scientific critique of the two-degree climate change target. *Nat. Geosci.*, **9**, 13–18, doi:10.1038/ngeo2595.

Kolstad, C., and Coauthors, 2014: Social, Economic and Ethical Concepts and Methods. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Kopp, R. E., and Coauthors, 2016: Temperature-driven global sea-level variability in the Common Era. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, E1434-41, doi:10.1073/pnas.1517056113. http://www.ncbi.nlm.nih.gov/pubmed/26903659 (Accessed April 9, 2017).

Krasting, J. P., J. P. Dunne, E. Shevliakova, and R. J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophys. Res. Lett.*, **41**, 2520–2527, doi:10.1002/(ISSN)1944-8007.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Clim. Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.

Krey, V., and Coauthors, 2014: Annex II: Metrics & Methodology. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1281–1328.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change*, **118**, doi:10.1007/s10584-012-0681-4.

Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Clim. Change*, **122**, doi:10.1007/s10584-013-0971-5.

Kriegler, E., and Coauthors, 2015: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change*, **90**, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E., and Coauthors, 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change*, **123**, doi:10.1007/s10584-013-0953-7.

Kriegler, E., and Coauthors, 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Chang.*, **42**, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.

Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Clim. Change*, **122**, 401–414, doi:10.1007/s10584-013-0971-5.

Kriegler, E., and Coauthors, 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*.

Kriegler, E., and Coauthors, 2015: Diagnostic indicators for integrated assessment models of climate policy. *Technol. Forecast. Soc. Change*, **90**, 45–61, doi:10.1016/j.techfore.2013.09.020. http://dx.doi.org/10.1016/j.techfore.2013.09.020.

Kriegler, E., and Coauthors, 2015: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change*, **90**, **Part A**, 24–44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E., and Coauthors, 2013: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The LIMITS Study on Durban Platform Scenarios. *Clim. Chang. Econ.*, **4**, 1340008, doi:10.1142/S2010007813400083. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400083.

Kunreuther, H., and Coauthors, 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Lackner, K. S., S. Brennan, J. M. Matter, A.-H. A. Park, A. Wright, and B. Van Der Zwaan, 2012: The urgency of the development of CO2 capture from ambient air. *Proc. Natl. Acad. Sci.*, **109**, 13156–13162. http://www.pnas.org/content/109/33/13156.short (Accessed April 21, 2015).

Lal, R., 2004: Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science (80-.).*, **304**, 1623 LP-1627. http://science.sciencemag.org/content/304/5677/1623.abstract.

Le Page, Y., and Coauthors, 2013: Sensitivity of climate mitigation strategies to natural disturbances. *Environ. Res. Lett.*, **8**, 15018, doi:10.1088/1748-9326/8/1/015018.

Le Quéré, C., and Coauthors, 2016: Global Carbon Budget 2016. *ESSD*, **8**, 605–649, doi:10.5194/essd-8-605-2016.

Leduc, M., H. D. Matthews, and R. de Elía, 2016: Regional estimates of the transient climate response to cumulative CO2 emissions. *Nat. Clim. Chang.*, **6**, 474, doi:10.1038/nclimate2913. http://www.nature.com/doifinder/10.1038/nclimate2913 (Accessed April 5, 2017).

Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions – A GDP scenario approach. *Glob. Environ. Chang.*, **42**, 215–225, doi:10.1016/j.gloenvcha.2015.02.005. http://www.sciencedirect.com/science/article/pii/S0959378015000242 (Accessed April 4, 2017).

Leon, J. X., J. Hardcastle, R. James, S. Albert, J. Kereseka, and C. D. Woodroffe, 2015: Supporting Local and Traditional Knowledge with Science for Adaptation to Climate Change: Lessons Learned from Participatory Three-Dimensional Modeling in BoeBoe, Solomon Islands. *Coast. Manag.*, **43**, 424–438, doi:10.1080/08920753.2015.1046808. http://www.tandfonline.com/doi/full/10.1080/08920753.2015.1046808.

Lowe, J. A., C. Huntingford, S. C. B. Raper, C. D. Jones, S. K. Liddicoat, and L. K. Gohar, 2009: How difficult is it to recover from dangerous levels of global warming? *Environ. Res. Lett.*, **4**, 14012, doi:10.1088/1748-9326/4/1/014012.

Lucon, O., and Coauthors, 2014: Buildings. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 671–738.

Luderer, G., R. C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, and O. Edenhofer, 2013: Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, doi:10.1088/1748-9326/8/3/034033.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Clim. Change*, **136**, 127–140, doi:10.1007/s10584-013-0899-9.

Luderer, G., R. C. Pietzcker, C. Bertram, E. Kriegler, and M. Meinshausen, 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033, doi:10.1088/1748-9326/8/3/034033.

Malhi, Y., T. a. Gardner, G. R. Goldsmith, M. R. Silman, and P. Zelazowski, 2014: Tropical Forests in the Anthropocene. *Annu. Rev. Environ. Resour.*, **39**, 125–159, doi:10.1146/annurev-environ-030713-155141. http://www.annualreviews.org/doi/abs/10.1146/annurev-environ-030713-155141.

Malm, A., and A. Hornborg, 2014: The geology of mankind? A critique of the Anthropocene narrative. *Anthr. Rev.*, **1**, 62–69, doi:10.1177/2053019613516291.

Manning, M., M. Petit, D. Easterling, J. Murphy, A. Patwardhan, H.-H. Rogner, R. Swart, and G. Yohe, 2004: *Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options*. https://www.ipcc.ch/pdf/supporting-material/ipcc-workshop-2004-may.pdf (Accessed April 5, 2017).

Mastrandrea, M. D., K. J. Mach, G.-K. Plattner, O. Edenhofer, T. F. Stocker, C. B. Field, K. L. Ebi, and P. R. Matschoss, 2011: The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Clim. Change*, **108**, 675–691, doi:10.1007/s10584-011-0178-6. http://link.springer.com/10.1007/s10584-011-0178-6 (Accessed April 5, 2017).

Matthews, H. D., and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, **35**, L04705, doi:10.1029/2007GL032388.

Matthews, H. D., N. P. Gillett, P. a Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459**, 829–832, doi:10.1038/nature08047. http://www.ncbi.nlm.nih.gov/pubmed/19516338.

Matthews, H. D., and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nat. Clim. Chang.*, **2**, 338–341, doi:10.1038/NCLIMATE1424.

McMillen, H. L., and Coauthors, 2014: Small islands, valuable insights: Systems of customary resource use and resilience to climate change in the Pacific. *Ecol. Soc.*, **19**, doi:10.5751/ES-06937-190444.

Meehl, G. A., and Coauthors, 2007: Global Climate Projections. *Methods*, **54**, 747–845. http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Meehl, G. A., J. M. Arblaster, and C. Tebaldi, 2005: Understanding future patterns of increased precipitation intensity in climate model simulations. *Geophys. Res. Lett.*, **32**, L18719, doi:10.1029/2005GL023680. http://acacia.ucar.edu/ccr/publications/2005GL023680.pdf (Accessed April 7, 2017).

Mimura, N., R. S. Pulwarty, D. M. Duc, I. Elshinnawy, M. H. Redsteer, H. Q. Huang, J. N. Nkem, and R. A. Sanchez Rodriguez, 2014: Adaptation Planning and Implementation. *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 1: Global and Sectoral Aspects*, Intergovernmental Panel on Climate Change, Ed., Vol. 1 of, Cambridge University Press, Cambridge, 869–898 https://www.cambridge.org/core/books/climate-change-2014-impacts-adaptation-and-vulnerability-part-a-global-and-sectoral-aspects/adaptation-planning-and-implementation/B3CA65055E980191D5FA4FFA3258C233.

Mitchell, D., and Coauthors, 2016: Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI): Background and Experimental Design. *Geosci. Model Dev. Discuss.*, 1–17, doi:10.5194/gmd-2016-203. http://www.geosci-model-dev-discuss.net/gmd-2016-203/.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *J. Geophys. Res. Atmos.*, **117**, doi:10.1029/2011JD017187.

Moss, R. H., and S. H. Schneider, 2000: *Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting*. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.399.6290&rep=rep1&type=pdf (Accessed April 5, 2017).

Myhre, G., and Coauthors, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 658–740.

Nakashima, D., K. Galloway McLean, H. Thulstrup, A. Ramos-Castillo, and J. Rubis, 2012: *Weathering Uncertainity: Traditional knowledge for climate change assessment and adaptation*. UNESCO and United Nations University Traditional Knowledge Initiative, 120 pp. http://collections.unu.edu/view/UNU:1511 (Accessed April 6, 2017).

Niang, I., O. C. Ruppel, M. A. Abdrabo, A. Essel, C. Lennard, P. J, and P. Urquhart, 2014: Africa. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part B Reg. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1199–1265.

O' Brien, K., and Coauthors, 2012: *Toward a sustainable and resilient future*. 437-486 pp. http://www.scopus.com/inward/record.url?eid=2-s2.0-84928068269&partnerID=40&md5=40c1ebdfdc987dcb9a81887c7908b2f4.

Okereke, C., 2010: Climate justice and the international regime. *Wiley Interdiscip. Rev. Clim. Chang.*, **1**, 462–474, doi:10.1002/wcc.52. http://doi.wiley.com/10.1002/wcc.52 (Accessed April 7, 2017).

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi, 2014: Emergent Risks and Key Vulnerabilities. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1039–1099, doi:10.1017/CBO9781107415379.

Otto, F. E. L., D. J. Frame, A. Otto, and M. R. Allen, 2015: Embracing uncertainty in climate change policy. *Nat. Clim. Chang.*, **5**, 1–5, doi:10.1038/nclimate2716. http://www.nature.com/doifinder/10.1038/nclimate2716.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The 2C capital stock for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Appl. Energy*, **179**, 1395–1408, doi:10.1016/j.apenergy.2016.02.093.

Planton, S., 2013: Annex III: Glossary. *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang. Panel Clim. Chang.*, 1447–1466.

Plattner, G. K., and Coauthors, 2008: Long-term climate commitments projected with climate-carbon cycle models. *J. Clim.*, **21**, 2721–2751, doi:10.1175/2007JCLI1905.1.

Raygorodetsky, G., 2011: Why Traditional Knowledge Holds the Key to Climate Change - United Nations University. *Clim. Chang. Cult. Relig.*,. https://unu.edu/publications/articles/why-traditional-knowledge-holds-the-key-to-climate-change.html (Accessed April 6, 2017).

Revi, A., D. E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R. Kiunsi, M. Pelling, D. Roberts, and W. Solecki, 2014: Urban areas. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability*. *Part A Glob. Sect. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 535–612.

Riahi, K., and Coauthors, 2015: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*.

Richardson, M., K. Cowtan, E. Hawkins, and M. B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. *Nat. Clim. Chang.*, **6**, 931–935.

Rockström, J., and Coauthors, 2016: The world's biggest gamble. *Earth's Futur.*, **4**, 465–470, doi:10.1002/2016EF000392.

Rogelj, J., and Coauthors, 2016: Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nat. Clim. Chang.*, **534**, 631–639, doi:10.1038/nature18307. http://0-www.nature.com.wam.city.ac.uk/nature/journal/v534/n7609/pdf/nature18307.pdf.

Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015: Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming. *Environ. Res. Lett.*, **10**, 75001, doi:10.1088/1748-9326/10/7/075001. http://stacks.iop.org/1748-9326/10/i=7/a=075001?key=crossref.f848653474225e744cc64bb0190b3170 (Accessed April 6, 2017).

Savo, V., D. Lepofsky, J. P. Benner, K. E. Kohfeld, J. Bailey, and K. Lertzman, 2016: Observations of climate change among subsistence-oriented communities around the world. *Nat. Clim. Chang.*, **6**, 462–473.

Schleussner, C. F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming : the case of 1.5◦C and 2◦C. *Earth Syst. Dyn.*, **7**, 327–351, doi:10.5194/esd-7-327-2016-supplement.

Schroeder, H., M. T. Boykoff, and L. Spiers, 2012: Equity and state representations in climate negotiations. *Nat. Clim. Chang.*, **2**, 834–836.

Seto, K. C., S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh, and D. Ürge-Vorsatz, 2016: Carbon Lock-In: Types, Causes, and Policy Implications. *Annu. Rev. Environ. Resour.*, **41**, 425–452, doi:10.1146/annurev-environ-110615-085934.

Shine, K. P., J. S. Fuglestvedt, K. Hailemariam, and N. Stuber, 2005: Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Clim. Change*, **68**, 281–302, doi:10.1007/s10584-005-1146-9. http://link.springer.com/10.1007/s10584-005-1146-9 (Accessed April 7, 2017).

Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. 366 pp.

Smith, P., and Coauthors, 2016: Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.*, **6**, 42–50, doi:10.1038/nclimate2870\rhttp://www.nature.com/nclimate/journal/v6/n1/abs/nclimate2870.html#supplementary-information. http://dx.doi.org/10.1038/nclimate2870.

Smith, S. M., J. a. Lowe, N. H. a. Bowerman, L. K. Gohar, C. Huntingford, and M. R. Allen, 2012: Equivalence of greenhouse-gas emissions for peak temperature limits. *Nat. Clim. Chang.*, **2**, 535–538, doi:10.1038/nclimate1496. http://www.nature.com/nclimate/journal/v2/n7/full/nclimate1496.html.

Smith, S. J., and P. J. Rasch, 2013: The long-term policy context for solar radiation management. *Clim. Change*, **121**, 487–497, doi:10.1007/s10584-012-0577-3.

Solomon, S., G.-K. G. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 1704–1709, doi:10.1073/pnas.0812721106. http://www.pnas.org/content/106/6/1704.short%5Cnhttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2632717&tool=pmcentrez&rendertype=abstract.

Stavins, R., and Coauthors, 2014: International Cooperation: Agreements and Instruments. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*,.

Stechow, C. von, and Coauthors, 2016: 2°C and the SDGs: United they stand, divided they fall? *Environ. Res. Lett.*, **11**, 34022, doi:10.1088/1748-9326/11/3/034022. http://dx.doi.org/10.1088/1748-9326/11/3/034022.

Stern, N., 2014: Ethics, Equity and the Economics of Climate Change Paper 1: Science and Philosophy. *Econ. Philos.*, **30**, 397–444, doi:10.1017/S0266267114000297. http://www.journals.cambridge.org/abstract_S0266267114000297.

Stocker, T. F., and Coauthors, 2013: Technical Summary. *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 33–115, doi:10.1017/ CBO9781107415324.005.

Stott, P., D. Stone, and M. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610–614, doi:10.1029/2001JB001029.

Tett, S. F. B., P. A. Stott, M. R. Allen, W. J. Ingram, and J. F. B. Mitchell, 1999: Causes of twentieth-century temperature change near the Earth's surface. *Nature*, **399**, 569–572, doi:10.1038/21164. http://www.nature.com/doifinder/10.1038/21164 (Accessed April 6, 2017).
The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. 1-5 pp.
UN, 2016: *Sustainable Development Goals*.
United Nations, 2015: *World Population Prospects - Population Division - United Nations*. 1-5 pp. https://esa.un.org/unpd/wpp/.
Voski, A., 2016: The Role of Climate Change in Armed Conflicts across the Developing World and in the Ongoing Syrian War. *Carlet. Rev. Int. Aff.*, **3**, 120–141.
World Health Organization, 2016: Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children. *WHO Guidel.*, doi:9789241565233. http://apps.who.int/iris/bitstream/10665/204717/1/9789241565233_eng.pdf?ua=1.
World Health Organization, 2016: *Ambient Air Pollution: A global assessment of exposure and burden of disease*. 1-131 pp. www.who.int.org.
Zickfeld, K., M. Eby, H. D. Matthews, and A. J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 16129–16134, doi:10.1073/pnas.0805800106.
Zickfeld, K., and Coauthors, 2013: Long-Term climate change commitment and reversibility: An EMIC intercomparison. *J. Clim.*, **26**, 5782–5809, doi:10.1175/JCLI-D-12-00584.1.

Chapter 2: Mitigation pathways compatible with 1.5 °C in the context of sustainable development

Coordinating Lead Authors: Kejun Jiang, Joeri Rogelj, Drew Shindell

Lead Authors: Solomone Fifita, Piers Forster, Veronika Ginzburg, Collins Handa, Haroon Kheshgi, Shigeki Kobayashi, Elmar Kriegler, Luis Mundaca, Roland Séférian, Maria Virginia Vilariño

Contributing Authors: Daniel Huppmann

Review Editors: Jan Fuglestvedt, Latifa Redani

Date of Draft: 6 April 2017

Executive Summary

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit global mean warming to 1.5 °C (relative to preindustrial base period defined in Chapter 1). Key questions addressed are: What types of mitigation pathways have been developed that could be compatible with 1.5 °C? What changes in emissions, energy and land use do they entail? What do they imply for climate policy, implementation, and sustainable development?

2.1.1 Mitigation Pathways compatible with 1.5 °C

- Define the notion of emissions scenarios (model-based consistent projection of future development of emissions and their drivers; these need to cover all sectors and regions over the 21st century to be associated with a climate change projection to 2100). Reference emission scenarios (e.g. current legislation or NDCs) lead to warming well above 1.5 °C, hence we examine mitigation pathways (a class of scenarios aiming at a normative end point specified by a climate target). Pathways developed with detailed modelling may also be classified as 'solutions pathways', i.e. constituting more than hypothetical thought experiments.
- Compatibility with 1.5 °C
- Emissions scenarios / Mitigation pathways can have a range of climate outcomes due to uncertainties in radiative forcing and climate response. They therefore cannot be mapped to a single warming level, but rather to a range of warming levels and probabilities of staying below them (e.g., AR5 WGIII SPM Table 1). In other words, a pathway that is consistent with 1.5 °C may still miss this target (in either direction, see also Section 2).
- Compatibility can be defined in multiple ways:
    - Limiting peak warming to 1.5 °C (expressed, e.g., in terms of maximum allowed 1.5 °C exceedance probability)
    - Timing of reaching a warming likely below 1.5 °C (expressed, e.g., as the time when exceedance probability drops below 34%)
    - Temporarily exceeding 1.5 °C (with more than some low probability p) and returning below 1.5 °C afterwards (with higher than some probability 1-p)
      Various lengths of overshoot (e.g. measured in terms of expected degree years. [Such a metric of the "overshoot intensity" may be useful for Chapter 3, likely provided in Chapter 1].

2.1.2 Contextualizing 1.5 °C pathways

- Concept of measuring policy impact relative to a reference case (e.g., emissions reductions, mitigation costs, etc.)
- Socio-economics underlying pathways/scenarios [see also Section 2.4]
  - Socio-economic drivers: population, consumption (goods & services, including food), economic growth, behavior, technology, institutions
  - Energy and land use: energy resources/energy supply technologies/end-use efficiency, energy demand, agricultural productivity, food demand, terrestrial carbon management, etc.
  - Climate policies: carbon pricing, technology policies, regional differentiation, etc.
  - Link to multiple drivers: GHGs, aerosol and ozone precursors, land-use/land-cover, contrails
  - Illustration of different pathways and aspects this chapter will consider

2.1.3 Sustainable development context of 1.5 °C and other mitigation pathways

- Climate protection as an aspect of sustainable development [brief mention of SDGs with reference to Chapter 5], optimization framework used in pathway generation
- Co-effects of mitigation on multiple other sustainable development goals and poverty eradication [broad high-level overview, framing of challenges and opportunities], relationship to framework used in pathway generation

2.1.4 New information and improved understanding since AR5

- Emissions, climate sensitivity, RF, development pathways, etc.
- Relation to AR6

2.2 Assessment methods

2.2.1 Relationship to AR5 and new scenario literature

This chapter provides an extension of the AR5 mitigation pathway assessment. It heavily relies on the integrated scenario literature, which the AR5 mainly discussed in Chapter 6 of its Working Group 3 contributions (Clarke et al. 2014). Since then, several new integrated multi-model studies have appeared in the literature that explore specific characteristics of scenarios markedly more stringent than the lowest scenario category assessed in AR5 (see Table 2.1). Those scenarios explore 1.5 °C pathways from multiple perspectives:

- Different assumptions about socio-economic drivers and developments including energy and food demand as, e.g., characterized by the shared socio-economic pathways (SSPs)
- Different assumptions about near term climate policies until 2020 and 2030 describing different levels of strengthening the NDCs
- Different assumptions about the availability of bioenergy and carbon dioxide removal technologies
- …

A large number of these scenarios were collected in a scenario database established for the assessment of this special report. It contains *x* 1.5 ° C scenarios, *y* well below 2 °C scenarios, and *z* scenarios with less stringent climate policies to allow putting 1.5 °C scenarios into context.

Table 2.1: New IAM studies that this chapter will draw upon and the key questions that can be explored by the scenarios of each study.

Study name	Key focus	Reference papers
SSPx-1.9	*Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W/m²*.	*(Rogelj et al, in review)*
ADVANCE	*Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020.*	*(Vrontisi et al, forthcoming)*
	Decarbonisation bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in	*(Luderer et al, forthcoming)*
CD-LINKS	*Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives.*	*(Krey et al, forthcoming); Coordinator: Riahi K.*
EMF-30	*Study of the contribution of short-lived climate forcers in deep mitigation scenarios*	*TBD*
EMF-33	*Study of the bioenergy contribution in deep mitigation scenarios*	*TBD*
CEMICS	*Study of CDR requirements and portfolios in 1.5 °C pathways*	*TBD*
To be continued		

2.2.2 Description of assessment tools and methods

2.2.2.1 Literature assessment

An assessment of the mitigation pathway literature that has appeared since AR5 lies at the core of this chapter. However, this chapter draws not solely upon IAM studies, but also upon the wider mitigation literature which looks at specific mitigation options in more isolated settings.

2.2.2.2 SSP framework

An important development in the recent scenario literature is the emergence of multi-model studies which use the framework of the Shared Socioeconomic Pathways (O'Neill et al. 2014). This framework, developed by the scientific community as an integrative framework for the assessment of mitigation and adaptation challenges (van Vuuren et al. 2014) provides harmonized input parameters and assumptions aligned with five broad narratives (O'Neill et al. 2017). [Maybe describe these narratives here in no more than 5 sentences in total.] These five SSPs allow for more systematic exploration of the impact of socio-economic development assumptions on mitigation and adaptation pathways. Socioeconomic drivers (population (KC and Lutz 2017), economic growth (Crespo Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017), urbanisation (Jiang and O'Neill 2017)) have been quantified for all SSPs and their general characteristics (Riahi et al. 2017) together with detailed energy system (Bauer et al. 2017), air pollution (Rao et al. 2017) and land use developments (Popp et al. 2017) have been described.

2.2.2.3 Integrated assessment models

Climate change is a global problem driven by societal activities at the regional and local scale. Climate policy needs to address these activities adequately and cover timescales of multiple decades to a century. Cross-scale and cross-sector policy analysis is hence required, which can be achieved by integrated assessment models (IAMs) of climate change. As a result, the main scientific tools underlying the literature assessed in this chapter are integrated assessment models (IAMs) combining a dynamic description of the coupled energy-economy-land-climate system and related energy-economy or land-economy models that allow a reasonable coverage of global greenhouse gas emissions from different sectors. Those models have grown more and more integrated so that the boundaries between different model classes have become increasingly fuzzy (energy system models, CGEs, economic growth models, land use and agriculture models, system dynamics models, econometric / Keynesian models etc.). The system coverage of integrated assessment models has also increased: many of them now include a process-based description of the land system in addition to the energy system, and some have been extended to cover air pollutants, water, and material use.

Discuss differences between process-based and cost-benefit IAMs (Weyant 2017) and their different uses. The pathways assessed in this chapter have been generated by process-based IAMs with only limited coverage of climate impacts.

Core assumptions, strengths, and limitations of IAMs and related models have been discussed in detail in AR5 WG3 6.2.1 (Clarke et al. 2014). These general characteristics have not fundamentally changed since then, if at all. However, in Table 2.2 we highlight key characteristics of IAMs and related models that play a particularly important role in the context of 1.5 °C scenarios. Since AR5, a harmonized model documentation of IAMs and underlying assumptions have been established (link to ADVANCE: http://www.fp7-advance.eu/content/model-documentation).

2.2.2.4 Geophysical assessment tools

The geophysical assessment in this chapter draws upon two classes of tools. First, there are insights derived from the most complex general circulation models (GCMs) or Earth system models (ESM), which simulate the fully coupled Earth system, including its atmospheric and ocean circulation, and land surface evolution and multiple biogeochemical cycles, like the carbon or the nitrogen cycle. Second, this assessment also makes use of reduced complexity or simple carbon cycle and climate models, like MAGICC (Meinshausen et al. 2011). These two classes of geophysical assessment tools come with their own strengths and limitations (see Table 2.2), but take up complementary roles. GCMs and ESMs reflect our most detailed up-to-date understanding of the Earth system. However, in doing so the computational cost of such tools is excessively high to assess a large ensemble of scenarios. Simple climate models hence provide a useful complement. Developed to closely emulate GCMs based on physical principles, they can be run multiple thousands of times without any restriction.

2.2.2.5 Other tools (if necessary)

Table 2.2: List of assessment tools, model characteristics of particular importance for 1.5 °C pathways, and a short discussion of them being fit for purpose. [All values are illustrative at the moment and not based on any assessment whatsoever.]

Assessment tool	Characteristics of particular importance for the assessment of 1.5°C pathways	Fit for purpose	Fitness score
Integrated Assessment Models			
CGE models			
	Interaction between sectors	*Some explanation*	+
	Disruptive change	*Some explanation*	+
	Contagion dynamics	*Some explanation*	-
	…		
Energy-economy models			
	Interaction between sectors	*Some explanation*	+
	…		
Hybrid models			
	Interaction between sectors	*Some explanation*	+
	…		
Decomposition analysis			
	…	*Some explanation*	
General circulation and Earth system models (GCMs and ESMs)			
	Reliable simulation of uncertain tipping elements	*Some explanation*	-
	Inclusion of our most detailed understanding of climate and carbon cycle feedbacks.	*Some explanation*	++
	Dedicated vetted simulations for 1.5°C available	*Some explanation*	+-
	…		
Reduced complexity (simple) climate models (MAGICC or even simpler)			
	Emulation of global mean temperature response of most complex models in mitigation scenarios.	*Some explanation*	++
	Representation of full assessed climate response uncertainties	*Some explanation*	+
	Stratospheric chemistry	*Some explanation*	+-
	Reversibility and carbon cycle response	*Some explanation*	+
	…		

2.2.3 The scenario approach

2.2.3.1 Pathway modelling as a discourse tool

Integrated assessment models provide maps of plausible futures to explore contingencies and pathways for international climate policy embedded in a broader "path-finding" discussion. To this end, IAMs may be seen as map making tools – used, for example, to generate a carefully crafted set of scenarios – to navigate the space of plausible futures between which to choose. Maps abstract from reality, and, as the history of cartography has shown, can be incomplete in many aspects and still be useful. Consulting an IAM is like consulting a map-making tool. It is useful if it produces the right kind of maps for the policy question concerned and the user knows how to read its maps with all their limitations." (ADVANCE)

2.2.3.2 What´s a scenario and how does it relate to "pathway"

"Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. The possibility that any single emissions path will occur as described in scenarios is highly uncertain" (Nakicenovic et al. 2000)
"Scenarios are stories that happened in the future." (http://www.forecastingprinciples.com/) The word pathway is often used interchangeably with the word scenario. However, pathways more often describe the clear temporal evolution of specific scenario aspects over time. For example, often the emissions pathway in line with a given scenario is referred to.

2.2.3.3 Types of scenarios

By varying scenario assumptions and scenario design, various types of scenarios can be constructed. This is important because the underlying narratives, assumptions and design of scenarios define to a large degree which questions can be addressed, for example, the exploration of implications of delayed climate mitigation action. In this assessment, we have identified the following classes of scenarios which are of particular interest to the questions addressed in this chapter: (a) scenarios with the same climate forcing target in 2100 but varying SSP assumptions; (b) pairs of 1.5 °C and 2 °C scenarios; (c) pairs of scenarios with stringent mitigation action after 2020 and with a path that follows the NDC until 2030; (d) …

2.2.3.4 Scenario assumptions

- SSPs, varying assumptions about population, economic development, inequality, technological development, climate policy potential, etc.
- Other core scenario assumptions, as far as not covered in AR5 or above.

2.2.3.5 Short explainer of what it means if a scenarios was feasible

- Ref. AR5 WG3 6.1.1, 6.2.4, where this is already explained.

2.2.3.6 Database, including reference (baseline)

- Introduction to the database
- Overview of the scenario ensemble for this assessment
- The scenario ensemble collected as part of Special Report on Global Warming of 1.5 °C process represents an ensemble of opportunity. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required.

2.2.4 Concept of consistent and required characteristics

Mitigation pathways generated with IAMs and related models describe an internally consistent and calibrated (to historical trends) way to get from current developments to meet long-term climate targets like the 1.5 °C limit. Characteristics of these pathways such as emissions reduction rates, time of peaking, low-carbon energy deployment rates can be assessed as being consistent with the 1.5 °C limit, if there is at least one or a few 1.5 °C pathways that exhibit these characteristics. However, they cannot be assessed for the required charateristics for reaching the 1.5°C limit, as there may be other 1.5°C pathways that do not exhibit these characteristics. In order to identify required characteristics, a targeted scenario analysis is needed that specifically asks the question if there could be pathways without the characteristics in question. This was done in AR5 for the question by which pathways have to obtain a peak in emissions to still be able to reach 2

°C, or which technologies are important to keep the 2 °C target within reach. In this assessment, we will distinguish between consistent and the much stronger concept of required characteristics of 1.5 °C pathways.

2.2.5 Risk management framing

2.2.5.1 Risk of failure to achieve pathway

Different pathways come with differing challenges to achieve them. These challenges are strongly determined by the underlying socioeconomic scenario assumptions of the pathways. The risk of failure to achieve a given pathway can thus also vary, even for pathways which, when successfully achieved, would result in the same climate outcome. For example, many 1.5 °C scenarios show strong societal rates of change to achieve stringent emissions reductions in the coming decades. As long as current societal trends are not in line with such strong rates of change, there is a high risk that such a pathway will neither be followed nor be achieved. Similarly, not reducing emissions over the next decades includes the reliance on as of today unproven technologies in the second half of the century. As long as the technical feasibility and societal sustainability of these technologies has not been clearly demonstrated, such pathways come with high risks of ultimately not being achieved.

[INSERT FIGURE 2.1 HERE]

Figure 2.1: Concept of figure illustrating risk of failure to achieve mitigation pathway and risk of failure to achieve desired temperature outcome.

2.2.5.2 Risk of failure to achieve desired outcome even if pathway is achieved

Even when assuming that a 1.5 °C mitigation pathway is successfully achieved, the uncertainty in the climate response still results in a range of potential temperature outcomes (for example, see also (Fawcett et al. 2015) for a similar point related to 2 °C). For example, the most stringent pathway shown in the Figure 2.2, keeps peak warming to below 1.5 °C with roughly 40%, but at the same time leaves a 10% chance that temperature peaks between 2 °C and 2.5 °C and also a non-zero chance that it is still higher. Assessment of impacts at 2 °C and higher levels are thus also of importance to understand the climate impacts under pathway with a median 1.5 °C temperature increase.

2.2.5.3 Adaptive management

Ultimately, it is unrealistic that any pathways starting today will be blindly followed until the end of the century. Society will adjust its response in response to new information. This adjustment can go in either direction. Earlier scenario studies have shown, however, that deeper emissions reductions in the near term hedge against the uncertainty of both climate response and technology availability.

2.3 Geophysical relationships and constraints

2.3.1 Introduction

Properties of the physical climate system are important for determining future emission pathways and their relationship with climate targets. This Section assesses the role of the physical characteristics of the climate system in setting carbon budgets, and plausible emission pathways, examining how they introduce constraints and add uncertainty.

2.3.2 Carbon budgets and contribution of non-CO_2 greenhouse gases and aerosols

AR5 WG1 (Collins et al. 2013) and AR5 WGIII (Clarke et al. 2014) presented slightly different versions of the carbon budget for staying below 1.5 °C and 2.0 °C temperature targets (see AR5 Synthesis report, Table 2.2). Differences primarily arose from different modelling approaches: WG1 based their analyses on complex climate model integrations of RCP scenarios. WGIII based their analyses on simplified climate models with a wide set of scenarios. Several modelling assumptions and physical science uncertainties are particularly important for the carbon budget when considering low emission pathways. These considerations are assessed here and carbon budgets are updated based on a) a reassessment of present day conditions, b) new emission pathways; c) updated knowledge of carbon cycle and temperature response. Differences in published carbon budget estimates also depend on what sort of budget is computed: threshold exceedance or threshold avoidance budgets (Rogelj et al. 2016b). This is particularly important when considering the impact of non-CO_2 forcing agents on either decreasing or increasing the available carbon budget. AR5 published threshold exceedance budgets.

[INSERT FIGURE 2.2 HERE]

Figure 2.2: Figure suggestion for Carbon budget. Provide a T vs cumulative C plot(s) for the sets of 1.5 and 2 °C pathways that are/will be available, zooming in on the under about 1200 GtC range and compare to AR5. Discuss in detail estimation of range and scientific uncertainty (recognizing the somewhat problematic description of uncertainty in the AR5) of the remaining C budget for T value. We might identify a few illustrative pathways with different characteristics that we would carry through the following sections.

Table 2.3: Carbon budget overview inspired by AR5 SYR Table 2.2

Cumulative CO_2 emissions from 1870 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

2.3.2.1 Improvements in understanding of geophysical processes since AR5

Summary of main areas in which new knowledge relevant to very low emission scenarios has emerged since AR5. Transient climate sensitivity (Tan et al. 2016; Shindell 2014; Sherwood et al. 2014; Zhai et al. 2015), radiative forcing of methane (Etminan et al. 2016), etc.. Revisit estimates of TCR, ECS enabling robust constraints on the carbon budget (Arain et al. 1994; Schneider et al. 2017; Gillett et al. 2013).
On ECS: New Armour Paper (accepted NCC and (Gregory and Andrews 2016)and submitted) revise low Otto-type ECS estimates upwards (as in other post-AR5 studies).

2.3.2.2 Geophysical basis for low emission pathway carbon budgets

The climate response of global mean surface temperature to cumulative CO_2 emissions can usefully be approximated by a linear relationship: the Transient climate Response to Cumulative CO_2 Emissions (TCRE) (Collins et al. 2013; Friedlingstein et al. 2014; MacDougall and Friedlingstein 2015). This simple idea forms the basis of a carbon budget approach when considering temperature targets. In real world applications, and especially for low CO_2 emission pathways the role of non-CO_2 forcing agents and emission pathways need to be considered, leading to different approaches to carbon budget estimates as either threshold exceedance budgets or threshold avoidance budgets (Rogelj et al. 2016b).

Work since AR5 confirms that within global carbon cycle models this relationship holds across a wide range of emissions (Leduc et al. 2016; Tokarska et al. 2016; Tokarska and Zickfeld 2015; Krasting et al. 2014; Frölicher 2016) and the theoretical understanding of why such relationship exists has been improved (Goodwin et al. 2014; Krasting et al. 2014). More important for low emissions is any pathway dependence in the relationship. Studies assessed in AR5 found the relationship to be more-or-less independent of pathway [e.g. Zickfield et al., 2012; Frohliher et al, 2014]. Studies since AR5 have confirmed that there is less pathway dependence within a single carbon-cycle model than structural uncertainty across models (Krasting et al. 2014), but some pathway dependence exists. Krasting et al. (2014) found that present day emission rates had a relatively low (~20% lower) TCRE within the GFDL-ESM2G model than either very low or very high emission rates. The time lag between emissions and response also needs to be considered when assessing pathway dependence. This lag has been shown to increase with the size of emission pulse (Zickfeld and Herrington 2015; Goodwin et al. 2014; Krasting et al. 2014; Matthews et al. 2009; Zickfeld et al. 2016). Generally, temperatures stay more or less constant for many centuries after CO_2 emissions reach zero (Collins et al. 2013; Nohara et al. 2015). This has led to carbon budget estimates which assume an instantaneous relationship between cumulative emissions and peak warming under low emissions pathways (Matthews et al. 2017). Yet, Krasting et al. (2014) point to the possibility of further warming on time scales of 100-200 year under pathways which follow present-day emission rates, increasing the pathway dependence of TCRE (also (Frölicher and Paynter 2015). The simple relationship also begins to breakdown in models which employ extensive carbon dioxide removal technologies. Despite these pathway specific caveats, TCRE is assessed to remain a good approximation, and applicable to low emission pathways.

TCRE can be estimated from coupled carbon cycle Earth System models and/or derived from combining simple models with the observational record. Collins et al. (2013) gave an estimate of 0.8 to 2.5 °C per 1000 PgC for the likely range based on an expert assessment. Simple model estimates gave slightly lower estimates TCRE in the simple models compared to more complex models (Gillett et al. 2013). The spread of TCRE estimates is only slightly affected by pathway dependence (see above). It mainly comes from uncertainty in how the surface temperature responds to CO_2 forcing and uncertainty in how the carbon cycle responds to emissions of CO_2.

Simple model estimates of TCRE are low when compared to complex carbon cycle models, likely in part due to relatively low historical estimated of Transient Climate Response (TCR) or Equilibrium climate Response (ECS) derived from Earth's energy budget changes, compared to when these emergent constraints are compared to models. Such estimates of ECS and TCR and the associated Attributable Warming Index depend on historic radiative forcings and temperature trends and have their own associated uncertainties.

2.3.2.3 Role of non-CO_2 gases and aerosols

This part evaluates how other contributors like aerosols and non-CO_2 GHG influence carbon budgets (Rogelj et al. 2015b). Forcing fraction of CO_2/total forcing in CMIP5 models compared to AR5 WG1 Chapter 8 (Myhre et al. 2013). Examine CO_2 vs non-CO_2 fraction in SSP pathways (https://tntcat.iiasa.ac.at/SspDb/, and particularly the 1.9 W/m^2 scenarios currently in review).

2.3.2.4 1.5 °C and 2 °C carbon budgets and their uncertainty

This part will assess carbon budget compatible with 1.5 °C or 2 °C in terms of:

- Net cumulative budget including (1) present SSP carbon budgets using MAGICC at 1.5 °C and 2.0 °C and (2) discussion about uncertainty in relation to TCRE, non CO_2 forcings above, increasing ECS with time (Armour, 2017, and earlier papers), land sink issues, permafrost/ESM feedbacks.

Allowable/Remaining carbon budget including present remaining SSP carbon budgets using MAGICC at 1.5 °C and 2.0 °C and assessment with relevant updates of major greenhouse gases budget at present day; for CO_2 (e.g., Le Quéré et al. 2016), for methane (Saunois et al. 2016), and future updated for N_2O. This description will be complemented with knowledge on fluxes (Ballantyne et al. 2015; Arneth et al. 2017). Influence of missing parts of carbon budgets like inland waters (Regnier et al. 2013; Borges et al. 2015) or coastal/blue carbon (Mcleod et al. 2011; Pendleton et al. 2012; Johannessen and Macdonald 2016).

[INSERT FIGURE 2.3 HERE]

Figure 2.3: idea: Uncertainties and constraints to the budget: something like Figure 3 from Knutti and Hegerl 2008 but showing unconstrained budget of CO2 at the top and squeezing more and more when other GHGs and uncertainties are added (maybe two figs – one showing squeezing and one showing uncertainty. Separate out (TCRE, Pathway, non-CO2 forcing?). Maybe another set of figs for remaining budget) maybe a bit like the following fig from Rogelj et al (2014) but include more uncertainties, not just ECS. [Link with Section 2.2]

2.3.3 Introduction to carbon and emissions neutrality, metrics

This subsection will focus on carbon neutrality in terms of emissions and carbon budget. Assessment will focus on:

- Amount of negative emissions to achieve carbon neutrality will be discussed here (Gasser et al. 2015).
- The role of cumulative and short-lived climate pollutants in pathways compatible with 1.5 °C or 2 °C and net zero emissions and their contribution to the radiative forcings (Bowerman et al. 2013; Allen et al. 2016)
- The use of climate metrics such as CO_2 equivalent, Global Warming Potential and Global Temperature Potential (Tanaka et al. 2009; Allen et al. 2016) to assess climate changes
- The link between climate pathways and sustainable development and how this relates to the use of metrics
- Implications of carbon neutrality in terms of long-term mitigation (Matthews and Caldeira 2008)
- (Gillett and Matthews 2010; Bowerman et al. 2011; Huntingford et al. 2012; Steinacher and Joos 2016; Allen et al. 2016)

2.3.4 Geophysical response to carbon dioxide removal: carbon cycle and temperature

Many of the scenarios discussed in this chapter include considerable amounts of CDR in their future pathways. Being part of negative emissions technologies (NETs), CDR are therefore present in the majority of AR5 scenarios that give a more than 50% chance of limiting warming to below 2 °C (Fuss et al. 2014a) and all scenarios that give more than a 50% chance of staying below 1.5 °C (Rogelj et al. 2015a). To date, most integrated assessment models have employed a limited range of technologies, typically bioenergy Carbon Capture and Storage (BECCS), see Section 5 in this chapter.

2.3.4.1 Effect on CDR to remove CO_2 from the atmosphere

Here, we assess the effect on the carbon cycle of the main CDR techniques that might be used at scale (The Royal Society 2009; Boucher et al. 2014; Hauck et al. 2016; Boysen et al. 2016; Heck et al. 2016b; Gasser et al. 2015; Wollenberg et al. 2016). We will include recent published methods like ocean alkalinisation (Ilyina et al. 2013) since AR5.

[INSERT FIGURE 2.4 HERE]

Figure 2.4: Idea: Bar chart with ΔCO2/ΔT effect and potential feedbacks on ΔCO2 derived from AR5 table (and ΔT if know/quantified feedback)

Table 2.4: Overview CDR characteristics, as in AR5 WG3, Table 6.15.

Table 6.15 | Characteristics of some CDR methods from peer-reviewed literature. Note that a variety of economic, environmental, and other constraints could also limit their implementation and net potential.

Carbon Dioxide Removal Method	Means of Removing CO_2 from Atmosphere	Carbon Storage / Form	Time Scale of Carbon Storage	Physical Potential of CO_2 Removed in a Century[a]	Reference	Unintended Side Effects
Afforestation and reforestation	Biological	Land /organic	Decades to centuries	40–70 PgC	House et al. (2002) Canadell and Raupach (2008)	Alters surface energy budget, depending on location; surface warming will be locally increased or decreased; hydrological cycle will be changed
Bio-energy with carbon-capture and storage (BECCS); biomass energy with carbon capture and storage	Biological	Geological or ocean /inorganic	Effectively permanent for geologic, centuries for ocean	125 PgC	See the footnote[b]	Same as above
Biochar creation and storage in soils	Biological	Land /organic	Decades to centuries	130 PgC	Woolf et al. (2010)	Same as above
Ocean fertilisation by adding nutrients to surface waters	Biological	Ocean / inorganic	Centuries to millennia	15–60 PgC 280 PgC	Aumont and Bopp (2006), Jin and Gruber (2003) Zeebe and Archer (2005) Cao and Caldeira (2010a)	Expanded regions with low oxygen concentration; enhanced N_2O emissions; altered production of dimethyl sulphide and non-CO_2 greenhouse gases; possible disruptions to marine ecosystems and regional carbon cycles
Ocean-enhanced upwelling bringing more nutrients to surface waters	Biological	Ocean / inorganic	Centuries to millennia	90 PgC 1–2 PgC	Oschlies et al. (2010a); Lenton and Vaughan (2009), Zhou and Flynn (2005)	*Likely* to cause changes to regional ocean carbon cycle opposing CO_2 removal, e.g., compensatory downwelling in other regions
Land-based increased weathering	Geochemical	Ocean (and some soils) / inorganic	Centuries to millennia for carbonates, permanent for silicate weathering	No determined limit 100 PgC	Kelemen and Matter (2008), Schuiling and Krijgsman (2006) Köhler et al. (2010)	pH of soils and rivers will increase locally, effects on terrestrial/ freshwater ecosystems
Ocean-based increased weathering	Geochemical	Ocean / inorganic	Centuries to millennia for carbonates, permanent for silicate weathering	No determined limit	Rau (2008), Kheshgi (1995)	Increased alkalinity effects on marine ecosystems
Direct air capture	Chemical	Geological or ocean /inorganic	Effectively permanent for geologic, centuries for ocean	No determined limit	Keith et al. (2006), Shaffer (2010)	Not known

2.3.4.2 Side-effect and geophysical limitation of CDR

We then review available estimates of needs in CDR to halt warming at a 1.5 °C level by 2100 (e.g. Gasser et al. 2015) and potential geophysical constraints related to the water availability (Heck et al. 2016a) and the nutrient availability.

2.3.5 Assessment of simple model performance in context of most recent literature

Simple models or emulator approaches such as MAGICC (Meinshausen et al. 2011), are used to estimate global and/or broad regional response patterns of the physical climate system to prescribed emission pathways. Assessment methods of these models differ from those used for complex comprehensive models as detailed in (Flato et al. 2013).

2.3.5.1 Tuning and calibration

Most IAM pathways considered in this chapter and throughout the report have used estimates of radiative forcing and global mean surface temperature derived from the MAGICC model, calibrated to previous CMIP phases of coupled model results (Meinshausen et al. 2011). Details on model calibration (e.g., use of AR4 models response and hence uncertainties relative to aerosols forcing) in light of known uncertainties and discrepancy of state-of-the-art ESMs will be assessed here (e.g., tuning on C4MIP with a too large sensitivity to rising CO_2 compared to CMIP5 models, or inter-dependence of tuning parameters). Calibration and tuning in terms of response to cumulative carbon emissions and committed warming levels. Here, we assess relevant studies comparing difference of behaviour between comprehensive ESMs and simple models to cumulative carbon emissions (Eby et al. 2013; Joos et al. 2013; Tokarska et al. 2016; Frölicher 2016; Zickfeld et al. 2016).

[INSERT FIGURE 2.5 HERE]

Figure 2.5: Calibration of MAGICC against CMIP3 AOGCM (from (Meinshausen et al. 2011) on global mean temperature using a subset of height parameters.

[INSERT FIGURE 2.6 HERE]

Figure 2.6: from (Geoffroy et al. 2015) using another climate emulator: illustration of trade-offs between calibration parameters to capture AOGCM (a) global mean temperature, (b) average sea surface temperature and (c) land-sea warming ratio.

2.3.5.2 Assessment in terms of carbon budget and temperatures outcomes

Comparison key climate and carbon outcomes estimated from simple models against those computed from comprehensive ESMs is an important consideration in the assessment of simple models. Here, we propose to assess both carbon budget and temperature outcomes relevant for low emissions scenarios as estimated from comprehensive ESMs and simple models (Rogelj et al. 2011; Jones et al. 2013) since the AR5 (Clarke et al. 2014).

[INSERT FIGURE 2.7 HERE]

Figure 2.7: Idea: it could be nice to update figure of carbon budget and temperatures outcomes with available results of rcp1.9 + rcp2.6 and SRES.

2.3.6 Pathway categorization in terms of temperature outcomes (peak and other)

As mentioned in AR5 WGIII, the definition of the temperature goals is complicated. This is especially the case with the long-term temperature goal (LTTG) defined within the Paris Agreement. Pending on the understanding of the Paris Agreement and the definition of 1.5 °C objectives defined and discussed in Chapter 1. We propose to classify temperatures outcomes in terms of time-scales associated with a given concentration of CO_2 (eventually carbon budget) and a probabilistic likelihood to exceed or avoid a given level of warming. We use the working definitions for a historical reference period (1861-1880), as defined in Chapter 1.

Throughout the Chapter we will be grouping/giving pathways by their temperature levels and probability. The method that we use and the rationale for that method will be explained here. If the method is different than that used in the AR5 WG3 approach, we explain why in detail and provide a comparison/translation of between the two methods. No new "IPCC" method or other metrics will be used (e.g. ECS distribution) unless there is a really compelling need (e.g. as opposed to identifying literature that suggest that one might reassess in the AR6).

2.3.6.1 Mid-term and transient likelihood of exceeding 1.5 °C or 2 °C

Here, we assess how pathways can be categorized in terms of temperature outcomes including those defined by avoidance or exceedance threshold relative to an overshoot (den Elzen and van Vuuren 2007; Lowe et al. 2009; Huntingford and Lowe 2007; Wigley et al. 2007). Mid-term temperature outcomes might be discussed in light of debate on natural variability (cf. AR5 WGI).

2.3.6.2 Long-term and equilibrium likelihood of achieving 1.5 °C or 2 °C

In this part, we assess literature which employ a probabilistic approach to estimates to reach 1.5 °C or 2 °C by 2100 (Tebaldi and Knutti 2007; Schleussner et al. 2016). Differences in terms of outcomes due to model approach or tools can lead to difference in terms of 2100 temperature outcomes. This is also the case when relying on MAGICC and probability distribution of input parameters, or on comprehensive ESMs. Studies focusing on temperature outcomes beyond 2100 will also be included in the assessment.

2.3.7 Overshoot, reversibility, feedback, temperature characteristics & extensions beyond 2100

The understanding of direct CDR impacts (e.g. on temperature and CO_2) and indirect impacts (hydrology, and other earth system components) has been improved since AR5 WGI report (Ciais et al. 2013), and additional studies have examined low carbon scenarios more generally. Based on the available literature, we propose to partition this section as follows.

2.3.7.1 Overshoot in temperature and CO_2

Most of the decarbonization pathways assessed in this chapter employ CDR and are likely to lead to overshoot of temperatures or carbon budgets (Rogelj et al. 2015a; Schleussner et al. 2016; Wigley et al. 2007; Huntingford and Lowe 2007). Since the thermal response of earth system is common to all CDR methods (Boucher et al. 2012), the magnitude of the temperature response is strongly related to the amount of CDR deployed in the emission pathways assessed in this chapter (Tokarska and Zickfeld 2015).

2.3.7.2 Tipping-point and feedbacks

In this part, we focus on tipping-point and feedbacks related to carbon cycle and extend to other biogeochemical cycles if relevant/available.

Several papers have pointed out cross-cutting issues relative to natural ecosystem-based CDR. They potentially concern relative weakening of the natural carbon sink (Jones et al. 2016) or contribution to natural disturbance (Le Page et al. 2013). Non-linear feedbacks, tipping points and slow onsets like permafrost thawing (Ranjan 2014; Friedlingstein et al. 2013; Jones et al. 2013) will be evaluated in this context. Studies focusing on the reversibility or hysteresis of the carbon cycle (Zickfeld et al. 2013) will be included in the assessment (accounting also forthcoming work from CDR-MIP).

2.3.8 How SRM affects carbon budgets, pathways and overshoots.

This subsection will assess relevant studies about SRM in the context of 1.5 °C or 2 °C. So far,Tilmes et al. (2016) have scoped their work in the context of 2 °C or 1.5 °C in terms of temperature outcomes.

In terms of carbon budget, SRM results in decrease of atmospheric CO_2 concentration in the atmosphere (MacMartin et al. 2016). SRM effects carbon budget by increase of carbon inflow to soil, but there are controversial conclusions about the influence of SRM on plants productivity. According to Mercado et al. (2009) and Xia et al. (2016) SRM leads to enhancement of terrestrial photosynthesis. Decreased temperatures will also enhance ocean CO_2 uptake and therewith acidification. Eliseev (2012) has showed that the mechanisms of the geoengineering effect on terrestrial carbon cycle characteristics are connected not with changes in solar radiation inflow at the surface, but mainly with the corresponding changes in the temperature humidity conditions in different regions and that SRM suppresses the gross primary production of plants and decreases the carbon stock in terrestrial vegetation. Anyway, generally all models show that geoengineering decelerates the increase of CO_2 concentration in the atmosphere. [Further impacts on acidification etc.]

[INSERT FIGURE 2.8 HERE]

Figure 2.8: Allowable carbon emissions induced by SRM in stratospheric injection of 4 TgSO2 per year from jan-2020 to dec-2069 (G4 GeoMIP). Total storage is partitioned into land biosphere storage (green) and ocean storage (blue). Grey bars indicate the amount of carbon released to the atmosphere 20 years after the cessation of the SRM (Plazzotta et al. in prep).

2.4 General characteristics of stringent global mitigation pathways

Setting the scene for the general whole-system transition characteristics of stringent global mitigation pathways. Much has been said in (Intergovernmental Panel on Climate Change 2015). A little repetition is required here to set the scene, but this should be limited to a minimum.

- Drivers: population, GDP growth, energy demand, food demand, …
- Supply transitions
- Demand transitions including behavioural change
- Systems thinking
- Key sectors: Energy, industry, agriculture (land), …
- Timing/phases

[Global emissions pathways, concentrations, and temperatures Rogelj, J., M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare, 2015: Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.*, **10**, 105007, doi:10.1088/1748-9326/10/10/105007. http://stacks.iop.org/1748-9326/10/i=10/a=105007.]

- QUESTION: do we want to say anything about regions here beyond highlighting that mitigation can be very different regionally?

[INSERT FIGURE 2.9 HERE]

Figure 2.9: Idea/concept: carbon intensity pathways for BAU, NDC targets and 1.5°C (like the one below for 2°C) as part of a larger mosaic figure. Issue to be resolved for such a figure, decarbonisation rates as computed in this figure become infinite as emissions become negative.

2.5 Transition characteristics of 1.5 °C pathways in the near-to-medium term

This section will present the pathway analysis of scenarios collected in the IPCC SR1.5 Scenario Database. A call for submissions and all infrastructure has been set up. Key studies have been contacted. The figures provide an idea of the kind of analysis that will be carried out. Scenarios will be grouped based on the 1.5 °C interpretations introduced in Chapter 1.

Please refer to Table 2.1 for an overview of the kind of scenarios that are expected to be submitted and the kinds of questions that can be addressed with the scenario ensemble.

Transition characteristics of 1.5 °C pathways from today until mid-century
- Emissions (CO_2, non-CO_2, gross CO_2, aerosols, …) in 2030 and 2050
- Context of NDCs based on published literature. A significant body of literature has been published following the Paris Agreement, which looks at estimating the emission consequences of the NDCs. Based on this literature the consistency of NDCs with 1.5°C pathways can be assessed. (Fujimori et al. 2016; Vandyck et al. 2016; Sanderson et al. 2016; Rogelj et al. 2016a; Iyer et al. 2015; Hof et al. 2017a; Rose et al. 2017; Fawcett et al. 2015)
- Concept of lock-ins, for example (Bertram et al. 2015a; Riahi et al. 2015; Johnson et al. 2015)
- Gap indicators in 2030
- Economics, incl. transitional costs, carbon price, investments and financing needs
- Policy and behavioural assumptions in the assessed scenarios

Disentangling the whole-system transformation (assessing and extracting indicators and variables)
Sectorial change and rates of change:
- Energy
- Industry
- Buildings
- Transport
- Land

- Demand/efficiency
- Relationships between sectors

Rates of change of key technologies and measures:
- Supply: CCS, bioenergy, renewables, nuclear, fossil energy (maybe stranded assets)
- Afforestation/reforestation
- CDR (BECCS, DAC)
- End-use technologies

[INSERT FIGURE 2.10]
Figure 2.10: (a)-(h)

[INSERT FIGURE 2.11]
Figure 2.11: (a)-(b)

2.6 Properties of 1.5 °C pathways after mid-century

All 1.5 °C and well below 2 °C emission pathways reach a point at which warming is stopped and often reversed. Since long-lived GHG accumulate in the atmosphere, their net emissions need to be brought to zero to halt their warming impact (Section 2.3) (Matthews et al. 2009). CO_2 is the dominant long-lived GHG, with significantly smaller climate forcing contributions coming from nitrous oxide, fluorinated gases and ozone-depleting substances (Myhre et al. 2013). Due to compensating contributions of committed warming and diminishing concentrations and forcing, the concept of a constant ratio of cumulative emissions of CO_2 to temperature holds well only until temperatures peak (Collins et al. 2013). It does not hold for stabilization on millennial time scales or for non- CO_2 forcings (Collins et al. 2013), because in the latter case the timescales of committed warming and diminishing forcing do not necessarily compensate.

Pathways keeping warming below a temperature limit have to attain at least net zero emissions in long-lived GHGs. This has been touched upon in the Paris Agreement calling for a “balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century” (Article 4, Paris Agreement), referring to all GHGs including long and shorter lived species. The timing of emissions neutrality (= net zero GHGs (Rogelj et al. 2015c)) is predominantly determined by the pace of bringing net CO_2 emissions to zero (= carbon neutrality) and even below zero to compensate for residual emissions of other long-lived GHGs (Fig. 2.12) (Rogelj et al. 2015c) as well as for potential residual warming of these species. This compensation mostly concerns nitrous oxide (N_2O) which continues to be emitted at substantial levels in most 1.5 °C pathways due to continued use of nitrogen fertilizer in agriculture including bioenergy (Figure 2.13a), but also the very long-lived fluorinated gases whose forcing only declines over timescales much longer than those of the temperature response of the climate system. If fully implemented, the Montreal protocol on phasing out ozone-depleting substances and its Kigali Amendment on phasing out hydrofluorocarbons, the largest and fastest growing group of fluorinated gases (Velders et al. 2015), will effectively limit the climate forcing from these substances. This is largely reflected in 1.5 °C pathways (Figure 2.13b), although 1.5 °C pathways might consider even deeper reductions than mandated by the Amendment. As shown in Figure 2.6.1, 1.5 °C pathways reach carbon neutrality between 2040 and 2050, depending on their different levels of stringency, following by net zero emissions of long-lived GHGs and emissions neutrality for all GHGs around 5-10 and 10-15 years later, respectively[1]. The point of peak warming in 1.5 °C pathways also falls into this timeframe. Carbon and emission neutrality occur around two to three decades earlier than in well below 2 °C pathways.

[1] The choice of metric to convert emissions of Non-CO_2 greenhouse gases into CO_2 equivalent emissions is not a large source of uncertainty for (long-lived) GHGs. Due to their long persistence time in the atmosphere, the values of their Global Warming Potentials (GWPs) and Global Temperature Potentials (GTPs) at 20 and 100 year time scales are similar (Myhre et al. 2013). We used the GWP100 metric for the assessment of emissions neutrality in long-lived GHGs in this chapter.

Warming levels are not only determined by long-lived GHGs, but also by emissions of short-lived climate forcers (SLCFs) with atmospheric lifetimes of up to about a decade. This category includes GHGs, like methane, and also air pollutants, like tropospheric ozone and black carbon. Due to their shorter lifetimes, their atmospheric concentration stabilizes (over time periods of years to decades) if their emissions are no longer increased. Changes in the emission rate of SLCFs thus translate quite directly into changes of radiative forcing and warming levels. In contrast to long-lived GHGs that accumulate in the atmosphere, emissions of shorter lived species thus do not need to be brought to zero to halt warming (Smith et al. 2012; Allen et al. 2016). In 1.5 °C pathways, SLCFs are reduced as deeply as possible based on the assumed abatement potentials in the underlying models and then remain fairly constant at these levels (Figure 2.13c). They reach their minimum levels by 2040-2050, around or before the time of carbon neutrality and peak warming. Because temperatures stabilize when emissions of short-lived climate forcers are kept constant, achieving emissions neutrality (= net zero GHG emissions, in which residual SLCF emissions are compensated by net carbon dioxide removal of CO_2) results in global temperatures slowly declining from the approximate peak level achieved due to net zero emissions of long-lived GHGs only.

SLCFs are also air pollutants and lowering their atmospheric concentrations is beneficial for reducing climate forcing as well as air pollution (Section 2.7 and Chapter 5; though other air pollutants such as SO_2 have a cooling impact and hence reductions increase overall climate forcing although they are beneficial for reducing air pollution). The extent to which short-lived climate forcing can be reduced overall has direct implications for the timing of carbon neutrality because the admissible amount of cumulated emissions under a temperature target (= emissions budget) is influenced by the remaining warming from non- CO_2 forcers, including SLCFs. Figure 2.13d provides an estimate of the remaining warming from residual SLCF emissions in 1.5 °C pathways assuming these minimum levels remain largely unchanged in longer term. Using the near-linearity between temperature increase and cumulative carbon emissions (Collins et al. 2013), this can also be converted into a rough estimate of the amount by which the carbon budget is reduced due to residual non- CO_2 emissions (ca. 200+/-40 $GtCO_2$ per 0.1 W/m^2). Note that the budget concept as defined in AR5 does not fully apply to other non- CO_2 GHGs, even if long-lived (Collins et al. 2013).

[INSERT FIGURE 2.12 HERE]

Figure 2.12: Time of warming peak vs. time of carbon neutrality across 1.5°C and well below 2°C scenarios.

[INSERT FIGURE 2.13 HERE]

Figure 2.13: Residual non CO2-emissions / forcing.

Different socio-economic systems consistent with 1.5 °C can be imagined, depending on the interpretation of what a “1.5 °C society” means. The latter question is a political question which we do not address here. Instead we assess the characteristics of various interpretations of 1.5 °C societies (Table 2.5).

Table 2.5: Characteristics of socio-economic systems consistent with low temperature goals, including 1.5 °C

	Residual emissions	**CDR requirement**
Keeping temperatures stable (at 1.5°C, but also any other low level)		
	Residual CO_2 emissions from hard to decarbonize activities like some industrial processes [some better examples]	CO_2 emissions removal required to compensate for residual emissions in order to achieve carbon neutrality
	Residual long-lived non-CO_2 GHGs	CO_2 emissions removal beyond carbon neutrality to compensate for warming due to continuing accumulation and committed warming of long-lived GHGs
	Deep reductions of SLCF emissions to stable minimum levels	No explicit CO_2 emissions removal requirement
Declining temperatures after an earlier higher peak		
	Residual CO_2 emissions from hard to decarbonize activities like some industrial processes [some better examples]	CO_2 emissions removal required to compensate for residual emissions in order to achieve carbon neutrality
	Residual long-lived non-CO_2 GHGs	CO_2 emissions removal beyond carbon neutrality to compensate for warming due to continuing accumulation and committed warming of long-lived GHGs
	Deep reductions of SLCF emissions to stable minimum levels	No explicit CO_2 emissions removal requirement
		Additional CO_2 removal beyond compensating for residual CO_2 and long-lived non-CO_2 GHGs. The annual rate pace of post-peak temperature decline is proportional to the annual amount of CO_2 removal.

Within these constraints, there are multiple emissions configurations that depend on socio-economic conditions, abatement potentials and policy choices. To start with, the more CO_2 and N_2O continue to be emitted, the more CO_2 needs to be removed annually from the atmosphere to compensate those residual emissions. The more residual emissions (and thus warming) from non-CO_2 forcers (including short and long-lived forcers) remain, the earlier the point of carbon neutrality needs to be reached. This has implications for the transition period including the deployment speed of low carbon energy, emissions abatement measures and potentially greenhouse gas removal (GGR) technologies in the first half of the century (Section 2.5). It may also increase the need for GGR to compensate an overshoot of the carbon budget. Figure 2.14a explores the role of carbon dioxide removal (CDR) in 1.5 °C and well below 2 °C pathways. About x-y % of CO_2 emitted from fossil fuel use, industrial processes and land uses is later removed from the atmosphere. x-y % of the removal occurs before reaching the point of carbon neutrality to accelerate the drawdown of emissions until mid-century. Another x-y % is used to compensate residual CO_2 emissions thereafter to maintain carbon neutrality. The remaining x-y % constitute net negative emissions reducing the peak amount of cumulative emissions to its 2016-2100 CO_2 budget level by x-y %.

Among those net negative emissions, x-y % compensate for residual emissions from long-lived GHGs other than CO_2, predominantly N_2O. The remaining x-y % of net negative emissions (x-y % of the total amount of CDR) are used to compensate excess emissions from earlier periods that led to an overshoot of the 1.5 °C consistent carbon budget, and to ensure forcing declines more rapidly than it would do through natural processes only. This function of negative emissions has received most of the attention in the literature since the Fifth Assessment Report of the IPCC (Fuss et al. 2014a) and was often connected to a concern that the expectation of CDR becoming available at large scale would postpone early mitigation efforts (Anderson and Peters 2016). Here we emphasize that CDR has multiple uses in low mitigation pathways. All the 1.5 °C pathways (x-y $GtCO_2$ during 2016-2100) and the largest majority of well below 2 °C pathways (0-y $GtCO_2$) assessed in this report deploy CDR at large scale, but there exists a considerable number of well below 2 °C and a small number of 1.5 °C pathway that restrict the use of CDR for compensating historic emissions from long-lived GHGs to 200 $GtCO_2$ or less If long-term residual SLCF emissions are completely phased out, the overall emissions budget for long-lived GHGs would increase sufficiently to eliminate the need for this particular use of CDR. [*will also include a discussion of minimum "CDR requirements" of 1.5 °C pathways based on a study in preparation exploring the trade-offs of limiting CDR in 1.5 °C pathways (Strefler et al.)*]

There are a number of approaches to actively remove CO_2 from the atmosphere. They include approaches to enhance terrestrial carbon storage in plants and soils (Lal 2004), such as afforestation and reforestation (Nilsson and Schopfhauser 1995), changing agricultural practices (Lal 2004), biochar sequestration (Smith 2016), and restoration of peatlands and wetlands. Other approaches aim to store atmospheric CO_2 in geological formations and include the combination of biomass combustion for energy production with carbon capture and storage (BECCS) (Obersteiner et al. 2001; Keith and Rhodes 2002) as well as direct air capture (DAC) of CO_2 using chemical solvents (Zeman and Lackner 2004; Keith et al. 2006). A third group focuses on the mineralization of atmospheric CO_2 (Mazzotti et al. 2005) including enhanced weathering of rocks (Hartmann et al. 2013). A fourth group is concerned with the sequestration of CO_2 in the oceans including ocean iron fertilization (Denman 2008) and ocean alkalinisation (Kheshgi 1995). A fifth group includes approaches to use atmospheric carbon in industrial products so that it is locked away on timescales of centuries (Carbon Capture and Usage – CCU; bioplastics, carbon fibre). There are also proposals to remove CH_4, N_2O and halocarbons via photocatalysis from the atmosphere (de_Richter et al. 2017). Only some of these approaches have so far been considered in integrated assessment and other pathway models.

The mitigation scenario literature up to AR5 mostly included BECCS and to a more limited extent afforestation and reforestation (Clarke et al. 2014). Since then, some well below 2 °C and 1.5 °C pathways including additional CDR options such as Direct Air Capture, Soil Carbon Enhancement and Enhanced Weathering have become available. Other more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. Figure 2.14b shows the deployment of individual CDR measures in 1.5 °C pathways. The largest contribution comes from BECCS (x-y $GtCO_2$) followed by afforestation (x-y $GtCO_2$) and direct air capture (x-y $GtCO_2$) when it is available. Making more CDR options available limits the use of individual CDR measures, but increases overall CDR use (Humpenöder et al. 2014).

Individual CDR options have different characteristics and therefore carry different risks for their sustainable deployment at scale (Smith et al. 2016). Terrestrial CDR options, BECCS and enhanced weathering of rock powder distributed on agricultural lands require land. DAC and BECCS rely on CCS and require safe storage space in geological formations. Some approaches like DAC have high energy and water demand. The sustainability implications of CDR options is discussed in greater detail in Section 2.7 and Chapter 5. Here we focus on some key properties of CDR deployment in 1.5 °C pathways that are relevant for the assessment of sustainability implications. Figure 2.15c shows the land requirements for BECCS and afforestation and Figure 2.15d the cumulative amount of CO_2 from BECCS, DAC and fossil fuel installations that is sequestered in geological formations. It can be seen that land demand for afforestation can be the most substantial [x-y Mha], since the amount of carbon that can be stored in soils and trees on one unit of land is limited to a fixed amount. Bioenergy plantations combined with CCS allow continuous sequestration of CO_2 from biomass year by year, but if deployed at scale still take up substantial land areas [x-y Mha]. If BECCS is available, most of the bioenergy use is combined with CCS (Rose et al. 2014). But large amounts of bioenergy are still used in similar if not larger amounts to substitute fossil-fuel based liquids, gases and solids if BECCS is not available (Klein et al. 2014). Bioenergy use would only be driven by BECCS, if in the absence of BECCS carbon neutral substitutes to biofuels were used preferably (see below). [*More results on bioenergy and BECCS in 1.5 °C pathways are expected from EMF33*]. In contrast to bioenergy use, CCS deployment is mostly driven by BECCS and, if available, DAC. They make up the largest share of CO_2 sequestration compared to CCS at fossil fuel installations [*quantify; compare with estimates of storage capacity*]. [*Potentials and limits of BECCS technologies, including land and feedstock required, to be assessed carefully*.]

Table 2.6: Source: IPCC Special Report (2005)

Table TS.6. Storage capacity for several geological storage options. The storage capacity includes storage options that are not economical.

Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

[a] These numbers would increase by 25% if 'undiscovered' oil and gas fields were included in this assessment.

[INSERT FIGURE 2.14 HERE]

Figure 2.14: Carbon Dioxide Removal CDR.

Table 2.7: Maybe also a table is useful here. Example Climate Action Tracker (2015)

	Until 2050 GtCO2	Until 2100 GtCO2
Total cumulative CO_2 storage capacity		
Returning warming to below 1.5°C by 2100 with 50% chance	135 (100-235)	790 (420-1070)
Holding warming to below 2°C during the 21st century with 66% chance	105 (75-170)	790 (555-990)
Cumulative storage capacity for CO_2 from biomass energy		
Returning warming to below 1.5°C by 2100 with 50% chance	45 (5-165)	520 (155-955)
Holding warming to below 2°C during the 21st century with 66% chance	22 (5-75)	440 (155-780)

Discussion of deep mitigation

- **Residual CO_2 emissions in industry, transport, residential and commercial sectors:** What is left after efficiency increase / demand reduction, electrification, and substitution of fossil based liquids / gases / solids in the sectors with bioenergy? Where are the decarbonisation bottlenecks? [*expect relevant publications from ADVANCE project*] How much do the pathways rely on bioenergy, how much on alternatives like hydrogen? The pathways in the largest majority describe a biofuel economy to overcome decarbonisation bottlenecks (Figure 2.15)
- **Deep mitigation options in the energy and industry sectors that are not yet considered in the pathway literature and which could make a difference to the residual emissions story:** Radical efficiency improvements [*need concrete examples of innovations and demand side measures which could shrink the supply side radically compared to available pathways*], expanding biofuel availability using algae, Power-to-X to produce carbon-neutral hydrocarbons (Zeman and Keith 2008), carbon fibre materials to replace steel and cement, etc.
- **The important role of land for an emissions neutral society:** carbon storage, bioenergy, making food production less land and GHG intensive etc.
- **Residual emissions from land use:** Limited abatement potential for non-CO_2 gases, particularly N_2O and CH_4 from agriculture (Gernaat et al. 2015). How to lower agricultural emissions further? Dietary changes, reduced food waste, changes in livestock management, supply side measures like changes to animal feed and rice cultivation and increased use of mineral fertilizer. Synthetic feed and meat.

[INSERT FIGURE 2.15 HERE]

Figure 2.15: Residual emissions and deep mitigation [based on suggestions from earlier reports and IEA]. (a) Sectorial CO2 and non-CO2 emissions in 2050 and 2100; (b) Electrification in sectors in 2050 and 2100; (c) Amount and composition of residual liquids / gases / solids use in sectors in 2050 and 2100; (d) Sectorial shares.

2.7 Co-impacts, opportunities, and challenges

Introduction and context:

- Guiding question: What are the most important implications of 1.5 °C mitigation pathways?
- Framing: Policies, non-climate impacts, co-impacts & trade-offs, potential opportunities and barriers (all timescales)

- Policies & institutional
  - Richness of policy portfolios and institutional structure
  - Level of ambition (modelling language in pathways)
  - CC and non-CC policies (development, health, poverty) integrated assessment
  - Links between innovation and mitigation policies
  - Market and behavioural failures (complement each other)
  - Trade-offs (e.g. environmental effectiveness vs. cost-effectiveness; deployment vs feasibility) and uncertainties
- Technology
  - Sufficiency of current technology, R&D in relation to (new) carbon budgets
  - supply vs. demand-oriented richness
  - Complexity to represent technology change (endogenous vs exogenous representation); adoption rates
  - Incremental costs
  - Empirical basis for parameterizing technological relationships
  - Risks and uncertainties for carbon, radiation and geo-eng. Technologies; including land-use and bionenergy
  - To question the economics of new long-lived energy infrastructure involving positive net emissions
- Behaviour
  - Social change, behavioural failures, assumptions and limitations
  - Psychological, motivational, knowledge and contextual factors
  - Integration into pathways and related modelling challenges
- Finance
  - Current resources/investment
  - Needed levels compatible with 1.5/SDGs (~GEA)
  - Climate finance (public and private)
  - Sources and intermediaries
  - Financial resource Gaps (sectoral basis)
- Socioeconomic and environmental issues
  - Economic indicators (e.g. aggregated mitigation costs, carbon market value, energy pricing)
  - Risks, uncertainties and benefits of CDR technologies
  - Damage functions are of low reliability and of poor empirical foundations
- Sustainable development implications of mitigation pathways
  - (Push conceptual/framework issues to Ch5; AR5 as departure point for assessing new quantitative studies)
  - Complex interactions, immaturity of models to capture C/B (in context of SD) (driven by knowledge gaps)

- Wider set of SD goals (beyond CC)
- Welfare and side-effects (e.g. job creation, energy security, air pollution, health impacts), linkages, potential materialisation and policy context
- Co-impacts (net positive or negative, multi-objective framework, assessment methodologies)
    - Risks and uncertainties under different structures (social, institutional, physical, technological)

2.7.1 Introduction

- Overall framing: policies, co-impacts, potential opportunities, barriers and trade-offs (all timescales, including development challenges). Guiding (ambitious/naïve) question: What are the most important implications of 1.5 °C-2 °C mitigation pathways, across Chapter 2? Focus: post-AR5 literature.
- All mitigation pathways presented in this chapter/section point in the same direction: they require accelerated and/or radical technological, economic, financial, institutional, political and behavioural change.
- A critical issue assumed but not explicitly treated in mitigation scenarios relates to needed behavioural change and leadership, and how to overcome behavioural failures.
- Despite uncertainty levels and model limitations, meeting the 1.5 °C-2 °C goal requires high urgency and deep transformation across technological, economic, financial, institutional, political and behavioural dimensions.
- Top-down approach to assess literature/issues and cross referencing with previous sections will be used. Aspects beyond modelling studies will be left to other Chapters (particularly Chapters 3, 4 & 5).

2.7.2 Policy and international governance

[*STORYLINE: The ultimate aim of the section is to briefly assess the policy features horizontally encompassed by recent studies (post AR5) addressing 1.5 °C (and 2.0 °C) mitigation pathways. A key focus will be on the richness of modelled policy portfolios, key assumptions (e.g. level of stringency), linkages with the Paris Agreement, carbon lock-in effects, etc. Depending on the level of disaggregation and scope of available studies, connections between climate policies (e.g. carbon tax) and non-climate policies (e.g. food security) will be analysed. Finally, and depending on available information, institutional aspects will be discussed, including barriers, and policy trade-offs confronted explicitly (e.g. environmental-effectiveness vs. political acceptability; higher near-term mitigation costs vs medium- and long-term expensive transitional technological challenges).*]

Overall, available studies show that mitigation pathways compatible with a 1.5 °C or 2 °C target require highly robust and ambitious policy regimes, which are often implemented at a global scale (e.g. carbon pricing mechanism). Policy assumptions play a critical role in linking socio-economic scenarios with economic and climate outcomes (Kriegler et al. 2014). In addition to stringency levels (tightened over time), critical policy issues driving results relate to compliance levels, international cooperation and political acceptability (Peters 2016; Riahi et al. 2017; Blanford et al. 2014; Kriegler et al. 2013). Highly ambitious policies targeting both the decarbonisation of the supply side and the reduction of energy use on the demand side play a major role across mitigation pathways (Rogelj et al. 2015a; Vandyck et al. 2016). However, policy-relevant details embedded in such studies, including assumptions, differ (e.g. specific type of policy instrument, related design, coverage and impacts on decarbonisation rates) and stylised policy categories are often found (Krey et al. 2014; Blanford et al. 2014; Peters 2016; Riahi et al. 2017). Whereas much of the modelling studies focus (implicitly or explicitly) on reducing or eliminating market failures (e.g. external costs, information asymmetries) via climate policy regimes, no study seems to address behavioural failures or anomalies from a policy perspective (e.g. bounded self-power, reference dependence).

There is also the need to explicitly address (and discuss) implementation limits and hurdles that socio-economic pathways and modelled scenarios entail from a policy point of view (Kriegler et al. 2014). Policy choice per se is acknowledged to be an important source of uncertainty (Rogelj et al. 2013a; Otto et al. 2015; Peters 2016). Scenarios that encompass weak and fragmented policy regimes, are unable to limit global warming below the 1.5 °-2 °C target or similar long-term climate targets (Luderer et al. 2016; Blanford et al. 2014), including INDCs (Rogelj et al. 2016a). Delayed action or weak near-term policies promote carbon lock-in effects and higher long-term mitigation costs (Seto et al. 2016; Bertram et al. 2015a; Kriegler et al. 2015a; Riahi et al. 2015; Luderer et al. 2016; Johnson et al. 2015). These scenarios use up a large share of the long-term cumulative carbon budget before 2030-2050, increasing the probability of exceeding the carbon budget in line 1.5 °or 2 °C target after 2030 (Vuuren et al. 2016; Bertram et al. 2015a). A relatively 'sub-optimal' policy mix implemented in the near term (2015-2030); encompassing a carbon price of US$7/ton CO2, minimum targets for low-carbon energy technologies, and a ban on new coal-based power plans, provide an opportunity to meet a 2 °C climate target (Bertram et al. 2015b). Nevertheless, a high global economy-wide carbon price is still needed in the long run (Bertram et al. 2015b). Moving from a 2 °C to a 1.5 °C target requires higher levels of stringency in the short run, so deep decarbonisation pathways can emerge and a net zero energy-economy system be achieved by 2040-2060 (Bataille et al. 2016; Rogelj et al. 2015a). Taking into account the 'carbon quota' concept in international climate policy (Raupach et al. 2014), there seems to be growing agreement to assess policies (e.g. INDC, carbon tax) from a probabilistic rather than deterministic perspective (Waldhoff and Fawcett 2011; Fawcett et al. 2015). If a 1.5 °-2 °C target is to be met, the complete avoidance of temporary overshooting arises as a plausible (global) policy scenario (Rockström et al. 2016).

Despite inherent levels of uncertainty attached to modelling studies (e.g. climate sensitivity, carbon cycle response), the urgency for decisive policy efforts to reduce GHG emissions in the short term remains very high (Rogelj et al. 2014). Modelling studies show that the window for meeting a 1.5 °C target by 2100 is closing very fast if weak policy regimes remain in place (Rogelj et al. 2015a; Luderer et al. 2013b). The literature shows different theoretical policy pathways that can eventually meet the 1.5°or 2°C mitigation target; however, current policy regimes and/or historical decarbonisation rates (sometimes incorporated in baseline or reference case scenarios) remain highly insufficient or inadequate to meet those targets in practice (Knutti et al. 2015; Sanford et al. 2014; Schleussner et al. 2016; Mundaca and Markandya 2016; Fawcett et al. 2015; Rogelj et al. 2016a) (see more details in Chapter 4).

Initial literature under review:

Bataille et al. (2016). The need for national deep decarbonization pathways for effective climate policy. *Climate Policy* 16 (S1):7-26.
Blanford et al. (2014). Harmonization vs. fragmentation: overview of climate policy scenarios in EMF27. Climatic Change 123 (3-4): 383-396.
Bertram et al. (2015). Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change* 5:235-239.
Fawcett et al. (2015). Can Paris pledges avert severe climate change? *Science* 350(6265):1168-1169.
Hallegatte et al. (2016). Mapping the climate change challenge. *Nature Climate Change* 6(7):663-668.
Hof et al. (2017). Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. *Environmental Science & Policy* 71:30-40.
Kriegler et al. (2013). What does the 2°c target imply for a global climate agreement in 2020? The limits study on Durban platform scenarios. Climate Change Economics 4(4):29pp
Kriegler et al. 82014). A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change* 122(3): 401-414.
Knutti et al. (2015). A scientific critique of the two-degree climate change target. *Nature Geoscience* 9:13-18.
Mundaca, L. & Markandya, A. (2016). Assessing regional progress towards a 'Green Energy Economy'. *Applied Energy* 179: 1372-1394.
Luderer et al. (2016). Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change* 136 (1): 127-140
Otto et al. (2015). Embracing uncertainty in climate change policy. Nature Climate Change 5: 917-920
Peters, G. (2016). The 'best available science' to inform 1.5 °C policy choices. *Nature Climate Change* 6:646-649.
Rogelj et al (2014). Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters* 9 (3): 7pp.
Rogelj et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5C. *Nature Climate Change* 5(6):519-527
Rogelj et al. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* 534: 631-639.
Riahi et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42:153-168.
Sanford et al. (2014). The climate policy narrative for a dangerously warming world. *Nature Climate Change* 4:164-166.

Schleussner et al. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change* 6:827-835.
Vandyck et al. (2016). A global stocktake of the Paris pledges: Implications for energy systems and economy. *Global Environmental Change* 41:46-63.

2.7.3 Technology and behavioural interplay

[*STORYLINE: This section aims to assess some overarching technological-behavioural issues associated with mitigation pathways studies. The integration of technology, societal change and behaviour will be assessed; including issues related to market and behavioural barriers or failures, assumptions and limitations (cross-reference with Section 7.2). Another area to be addressed relates to the richness of supply and demand-side technology in modelling studies. The section will discuss mitigation technologies in relation to the needed legislative environment for delivering profound social and behavioural change. In the long run, findings from Sections 2-6 will be critical to enrich the aspects contained in this section.*]

The bulk of 1.5 °-2 °C modelling studies relies heavily on IAMs (methodological details in Section 2), which have become increasingly popular to inform policymakers about the consequences of climate change. So far, limited (if any) integration of social sciences can be discerned in the modelling mitigation pathways literature. Given the embedded economic (optimisation) basis for technology choice, the objective function in IAMs aims to minimise the aggregate economic costs of achieving given mitigation outcomes (Clarke et al. 2014). In turn, modelling outcomes relied on 'Rational Choice Theory' (Goode 1997; Coleman and Fararo 1992; Karen C. et al. 2014) and engineering-economy determinants for technology choice, which assumes homogenous energy users with clear preferences, perfect information, unbounded rationality, etc. These aspects limit our understanding, treatment and potential effects of behavioural change and social and cultural challenges in technology mitigation pathways (Mundaca et al. 2016; Kolstad et al. 2014; Seto et al. 2016) [*Box "Energy Efficiency Gap" as example to show gap between models and empirics - joint Chapter 2 and 4*].

Methodological details are also needed concerning how analysed policies are supposed to reduce or eliminate market and behavioural failures in practice. However, a paramount issue from a methodological point of view is to what extent a representation of (empirically estimated) behavioural determinants of technology choice is actually feasible in IAMs. At all events, mitigation studies addressing behavioural options are emerging (not necessarily in the specific context of 1.5 °-2 °C target though) and show several opportunities for energy use conservation and emission reductions (Dietz et al. 2009; Faber et al. 2012; Abrahamse et al. 2005; Stern et al. 2016; Seto et al. 2016). Behavioural science, environmental psychology and randomized control trials (RCTs) provide alternative avenues to assess behavioural-based mitigation policy options and complement technology-based IAMs outcomes (see details in chapter 4).

Negative emission technologies play a key substantial role in the implementation of emission pathways and have a strong impacts on target viability (Luderer et al. 2013a; Kriegler et al. 2013). At the risk of oversimplifying, stringent long-term stabilisation targets combined with weak near-term policy scenarios yield an unprecedented deployment of negative emissions in the long term; resulting also in stranded investment in fossil-based infrastructure and higher mitigation costs —among several other aspects (see details in sections 5 and 6). However, there are growing concerns in the scientific community about the risks and uncertainties related to such technologies since AR5; particularly for BECCS and the required social and environmental change to accommodate such a large deployment (Fuss et al. 2014b; Anderson 2015a,b; Sanford et al. 2014; Rockström et al. 2016; Fuss et al. 2014a) (see also Chapter 4). Mitigation pathways compatible with a 1.5 °-2 °C call for an exceptional enlargement of biosphere carbon uptake (Rockström et al. 2016), massive market uptake of low-carbon technologies (Vuuren et al. 2016), and profound social and economic innovations (Boucher et al. 2016; Peters et al. 2013). These aspects impose unprecedented intra- and intergenerational policy and geopolitical challenges (see Chapter 4).

Initial literature under review:

Anderson, K. (2015). Duality in climate science. *Nature Climate Change* 8:898-900.
Anderson, K. (2015). Talks in the city of light generate more heat. Nature 528 (7583): 437
Bertram et al. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies.

Technological Forecasting and Social Change 90 (Part A):62-72.
Dietz et al. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences* 106(44):18452-18456.
Diffenbaugh, N. & Charland, A. (2016). Probability of emergence of novel temperature regimes at different levels of cumulative carbon emissions. *Frontiers in Ecology and the Environment* 14(8):418-423.
Faber et al. (2012). Behavioural climate change mitigation options and their appropriate inclusion in quantitative longer term policy scenarios. CE Delft, Fraunhofer ISI, LEI Wageningen. ML-30-13-627-EN-N.
Fuss et al. (2014). Betting on negative emissions. Nature Climate Change 4(10):850-853.
Johnson et al. (2015). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change* 90 (Part A):89-102.
Kriegler, et al. (2014). "The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies." *Climatic Change* 123(3-4): 353-367.
Kriegler et al. (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change* 90 (Part A): 24-44.
Peters et al. (2013). The challenge to keep global warming below 2 °C. *Nature Climate Change* 3(1):4-6.
Riahi et al. (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change* 90 (Part A): 8-23.
Rockström et al. (2016). The world's biggest gamble. Earth’s future 4(10): 465-470.
Rogelj et al. (2015). Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters* 10(7):14pp.
Rogelj, et al. (2015). "Energy system transformations for limiting end-of-century warming to below 1.5°C." *Nature Clim. Change* 5(6): 519-527.
Rogelj et al. (2013). 2020 emissions levels required to limit warming to below 2°C. *Nature Climate Change* 3(4): 405-412.
Smith et al. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change* 6(1):42-50.
van Vuuren et al. (2016). Carbon budgets and energy transition pathways. *Environmental Research Letters* 11:12pp.
Widerberg, O. & Pattberg, P. (2017). Accountability Challenges in the Transnational Regime Complex for Climate Change. *Review of Policy Research*. 34(1):68-87.

2.7.4 Economics and financial issues

[<u>*STORYLINE*</u>*: The aim of this section is to critically assess economic and financial issues associated with mitigation pathways. Particular attention will be given to methodological issues and uncertainty levels driving or framing macroeconomic cost and benefits (if any) (cross reference with Sections 2-6 and Chapters 3, 4 and 5). In addition, climate-related finance has been a central issue in international climate negotiations and one wonders what the exiting literature says about, for instance, the magnitude and timing of needed financial resources for meeting the 1.5 °C target. Building upon Sections 2-6, what can be said, for instance, about the sources, volume and use of (current and future) financial resources for an effective transformation? Depending on the geographical resolution of modelling studies, this sub-section will look into financial flows between countries/regions (i.e. where mitigation takes place and who pays for it) and potential implications for international distribution of wealth. From a pure economic point of view, the section will assess the range of mitigation costs and benefits (cross-ref with Chapter 3 and Chapter 5). Taking into account that economic damage functions in IAMs are of low reliability and, naturally, with weak empirical foundations, the section will identify uncertainties and any methodological improvement (and corresponding estimates) since AR5 (e.g. treatment of labour productivity, value of capital stock and ecosystem services). Likewise, and considering that mitigation costs are borne today but benefits take place in the long-term, attention will be given to discount rates (cross-reference with Chapter 3) when assessing mitigation costs in an intergenerational context - an issue that has been highly debated since AR4.*]

An early review of 1.5 °-2 °C modelling studies indicate that climate change will cause (considerable) economic damage if weak near-term policies remain in place. Considering the social costs of climate change (see Chapter 3) and potential co-impacts of climate mitigation in the context of sustainable development (see Section 7.5 and Chapter 5), immediate action is economically beneficial (Revesz et al. 2014; Moore and Diaz 2015). Whereas baseline or references scenarios do not entail mitigation costs (and e.g. related CDR technology co-impacts), they do encompass economic costs and risks associated with human and natural capital (e.g. water availability, food security, air quality, energy access) (see Chapters 3 and 5). Both mitigation costs and benefits are highly sensitive to input model assumptions (e.g. damage cost functions, carbon cycle response, non-CO_2 and land use CO_2 emissions abatement), the structure of methodological tool(s) and related uncertainty levels (see details in section 2) (Hof et al. 2017b; Clarke et al. 2014; Kolstad et al. 2014). When empirical or better estimates of temperature effects on GDP growth rates are included in 2 °C modelling studies (Moore and Diaz 2015), the social costs of carbon emission are several times higher than previous estimates (Revesz et al. 2014).

However, benefits of climate mitigation action (e.g. avoided negative externalities) appear to be less prominent in the literature. This may be largely explained because the majority of existing IAMs do not have a representation of climate damages (Kolstad et al. 2014; Clarke et al. 2014). When estimated, benefits of climate change mitigation are also likely to be undervalued due too, for example, the omission or limited inclusion of vulnerability of societies and economies to temperature changes and catastrophic climate change; treatment of human welfare losses due to lower development opportunities; damages to labour productivity, productivity growth and value of capital stock; and the use of a constant value attached to ecosystem services, which is unlikely to hold in the future because of climate impacts (e.g. water scarcity); and the use of a constant discount rate (often in the proximity of 5%) (Revesz et al. 2014). For the latter, there is agreement in the economic literature that that a declining discount rate over time should be used instead (Weitzman 1998; Arrow et al. 2013; Kolstad et al. 2014), this is regardless of the empirical consumption or investment-based approach used to estimate the discount rate. The use of a discount rate that declines over time yields a higher present value for the long-term impacts of global warming (e.g. floods, food security, water availability) and therefore a larger estimate for the social costs of increased GHG emissions (Revesz et al. 2014).

Key areas of uncertainties entail the magnitude of climate change impacts on economic growth (see Chapters 3 and 5), societal and infrastructure adaptation rates (see Chapters 1 and 3), and the dynamic interaction between economic damages and GDP (see Chapters 4 and 5) (Diffenbaugh and Charland 2016; Moore and Diaz 2015). Given the issues mentioned above, there appears to be limited methodological progress regarding the level of reliability and empirical foundations of economic damage functions associated with climate change (Moore and Diaz 2015) and their integration into a wider set of IAMs. Enhancing the capabilities of IAMs to address the benefits of climate mitigation seems to be a must (Revesz et al. 2014).

When it comes to mitigation costs as such, estimates vary widely and appear to be very sensitive to socio-economic assumptions and data related to energy sector technology portfolios (see details in Sections 5 and 6). Different metrics are used (e.g. fraction of baseline GDP, differential effects between first-best (optimal) policy and second-best (sub-optimal]) policies), which makes the comparisons more cumbersome (Clarke et al. 2014; Krey et al. 2014). In addition, there appears to be a higher number of 2 °C modelling studies/scenarios compared to 1.5 ° analyses. Comparison of mitigation costs thus have to be aware of the potential of sampling bias (Tavoni and Tol 2010). Nonetheless, keeping in mind the issues mentioned above, mitigation costs increase considerably when moving from a 2 °C to a 1.5 °C target (Luderer et al. 2013a), and even more when negative emission technologies (e.g. BECCS) are exogenously limited or unavailable.

Failure to adopt strong and effective policies in the near term (2020-2030) imply stranded investment in fossil-based capacity and steeper costly reductions in the long term (Johnson et al. 2015; Luderer et al. 2013a, 2016). Even in the presence of weak near-term policies, increased energy efficiency lowers mitigation costs considerably though (Bertram et al. 2015a). Furthermore, the analysis of Paris pledges shows relatively small losses in GDP, suggesting that international efforts to reduce GHG emissions is consistent with economic growth (Vandyck et al. 2016). A constant discount rate in the range of 5-7 % is often identified in the 1.5 °-2 °C literature (Blanford et al. 2014; Kriegler et al. 2015b; Rogelj et al. 2015a). This has relevant implications for intertemporal cost aggregation (Nordhaus 2007; Dietz and Stern 2008) (e.g. relatively lower discount rates yield higher mitigation costs because of the weight given to long-term mitigation costs). For impacts that are highly uncertain and taking place far in the future (e.g. 40 to 80 years from now), declining discount rates should be used and sensitivity analyses performed (Nordhaus 2013; Arrow et al. 2013; Nordhaus 2007). However, the discount rates used in cost-effectiveness frameworks (Blanford et al. 2014b; Kriegler et al. 2015b; Rogelj et al. 2015c), should not be confused with those used in cost-benefit frameworks, where also future impacts are added to the overall cost function.

Regarding finance, all reviewed modelling studies (so far) assume unlimited available resources (details of assumptions in Section 2). No financial crises or business cycles are modelled with IAMs and there is no distinction between public and private funding sources. Furthermore, no financial flows between countries/regions are identified. This prevents assertions about potential implications for international distribution of wealth (see Chapter 4). However, a (substantial) financial gap can be recognised in the literature. Whereas economic pathways that are compatible with the sustainable development goals, including climate mitigation, indicate that global investments in low-carbon energy systems need to be of the order of US$1.7-2.2 trillion per year (Riahi et al. 2012) (see details in Chapter 5), energy investment levels of approximately US$1.8 trillion were estimated for 2015 (IEA 2016). These figures also need to be compared with US$100 billion a year that has been allocated to climate finance for developing countries under the Paris Climate Agreement (see details in Chapter 4). Taking into account the estimated carbon lock-in effects and resulting mitigation costs (Bertram et al. 2015a), there is growing attention to the broader implications of asset stranding and financial stress tests for new energy infrastructure involving positive net emissions (details in Chapter 4). On a sectoral basis, and when a 2°C target is considered, quantitative studies show that no new emitting electricity infrastructure can be built after 2017 (Pfeiffer et al. 2016).

Table 2.8: concept

	Renewables	Nuclear	CDR	Dietary change	Clean Cooking/ heating/lighting	SRM
Potential GtC reduction	80/160		200	20	20	?
Challenges						
Techincal	Low/High	Low	High	None	Low	High
Behavioral	Low	Low	Low	High	Medium	Low
Governance	Low	High	Low	?	Medium	HIgh
Social acceptance	Medium	High	Low	High	Medium	High
Cost	High?	High	?	Low	Low	?
Opportunities						
Human Health	High (AQ)	High (AQ)	Low	High (diet)	High (AQ+gender)	Low
Food	Medium	Medium	Low/Neg.	High	Medium	Low/Neg.
Water	High	Low	Low/Neg.	High	Low	?

Initial literature under review:

Arrow et al. (2013). Determining Benefits and Costs for Future Generations. *Science* 341(6144): 349-350.

Busch et al. (2016). Sustainable Development and Financial Markets: Old Paths and New Avenues. *Business & Society* 55(3): 303-329.

Clarke et al. (2014). Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IEA (2016). *World Energy Investment Outlook*. Paris: IEA/OECD.

Johnson et al. (2015). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change* 90 (Part A):89-102.

Kolstad et al. (2014). Social, Economic, and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kriegler et al. (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change* 90 (Part A): 24-44.

Kroll, M. (2016). *Financing the 1.5C limit*. Future Finance - Policy Brief. World Future Council. 11/2016.

Luderer et al. (2013). Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters* 8:8pp.

Moore, F. & Diaz, D. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change* 5:127-131.

Nordhaus, W. (2013). *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. New Haven: Yale University Press.
Dietz, S. & Norhaus, W. (2008). Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Review of Environmental Economics and Policy* 2(1):94-113.
Pfeiffer et al. (2016). The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy* 179: 1395-1408.
Revez et al. (2014). Global warming: Improve economic models of climate change. Nature 508(7495): 173-175.
Riahi et al. (2012). Chapter 17 - Energy Pathways for Sustainable Development. In *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1203-1306.
Riahi et al. (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change* 90 (Part A): 8-23.
Riahi et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42:153-168.
Rogelj et al. (2013). The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2 °C. *Nature Climate Change* 3: 545-551.
Rogelj et al. (2013). Probabilistic cost estimates for climate change mitigation. *Nature* 493(7430): 79-83.
Seto et al. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources* 41:425-452.

2.7.5 Sustainable development and mitigation pathways

[*STORYLINE: The objective of this section is to quantitatively evaluate sustainable development issues, beyond climate mitigation, that are analysed in the post AR5 literature. Conceptual issues and analytical frameworks will be left to Ch5 and the focus will be on quantitative implications of mitigation pathways as far as sustainable development issues (e.g. SDG) are concerned. Studies with a multi-objective analytical framework will be of prime importance. Welfare and side-effects (e.g. job creation, energy security, air pollution and health impacts) will be considered (perhaps in specific sections depending on the wealth of information), including sectorial aspects. Whenever available, integrated modelling studies addressing multiple SD policy objectives will be analysed, including the complex interactions and feedback loops that emerge when multiple policy objectives exist (or need to be met). Attention will be given to co-impacts of mitigation pathways and whether they are net positive or negative in terms of welfare effects. Depending on the available data, aggregated policy costs (and benefits?) of meeting different SD policy objectives will be compared. Similarly, this sub-section will look into mitigation pathways that maximise synergies and minimise trade-offs. Risks and uncertainties under different structures (social, institutional, physical, and technological) will be highlighted*.]

Since AR5 , there is an increasing number of modelling studies showing that sustainable development objectives and climate policy targets are interrelated, and that synergies are found; however, trade-offs do exist (Jakob and Steckel 2016; Stechow et al. 2016). Synergies often found in the literature include, e.g. air quality, ocean acidification, oil security, water use, biodiversity, health impacts, fuel poverty and job creation. Nonetheless, studies seem to address a narrow subset of potential co-impacts in line with a 2 °C target. For instance, modelling efforts show that a 2 °C target is compatible with the UN's 'Sustainable Energy for All' initiative (Rogelj et al. 2013b), which encompasses increased energy access, renewable energy and energy efficiency. Identified co-impacts also include poverty alleviation, improved energy security and public health. Public health impacts have also been quantified for US emissions reductions consistent with a 2 °C target (West et al. 2013). Results show fewer premature deaths by 2030 (120,000-170,000) and national benefits in the range of 140-1,050 billion per year, which exceeds policy implementation costs (Shindell et al. 2016). As far as the energy-water use nexus is concerned, 2 °C scenarios show that global freshwater consumption increases because of rapidly growing electricity demand in developing regions and the dominance of freshwater-cooled thermal power generation (Fricko et al. 2016). In addition, it is argued that a 2 °C target could exacerbate the risks associated to hydropower, particularly in less industrialised countries (Hermoso 2017). When it comes to agriculture, it is shown that the climate path and the agriculture path are not necessarily the same due to CO_2 fertilization not being present for CH_4, HFCs, N_2O, etc (Shindell 2016). Mitigation costs can vary significantly when climate and sustainability scenarios are simultaneously assessed (Jakob and Steckel 2016). Results show that weak policy regimes entail fewer synergies and more trade-offs between climate mitigation and sustainability goals (Stechow et al. 2016). Trade-offs often arise from constraining a given mitigation technology (and its related risks, e.g.

CCS) and risks associated with climate impacts per se (e.g. water scarcity) and the deployment of other low-carbon technologies (e.g. nuclear power) (Jakob and Steckel 2016; Stechow et al. 2016). Demand-side management appears to play a critical role to produce synergies and manage identified trade-offs (Stechow et al. 2016; Fricko et al. 2016). Studies call for an integrated assessment framework to simultaneously evaluate climate and sustainable development policies (Griggs et al. 2014; Stechow et al. 2016) (see details in Chapter 5).

[INSERT FIGURE 2.16]

Figure 2.16: Figure concepts: Non-climate implications of climate policy. Source: (Jakob and Steckel, 2016).

Initial literature under review:

Fricko et al. (2016). Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters* 11:10pp

Grigggs et al. (2014). An integrated framework for sustainable development goals. Ecology and Society 19(4):49.

Hermoso, V. (2017). Freshwater ecosystems could become the biggest losers of the Paris Agreement. *Global Change Biology* (In press). doi 10.1111/gcb.13655

Jakob, M. & Steckel J.C. (2016). Implications of climate change mitigation for sustainable development. *Environmental Research Letters* 11:9pp.

Rogelj et al. (2013). The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2 °C. *Nature Climate Change* 3: 545-551.

Riahi et al. (2012). Chapter 17 - Energy Pathways for Sustainable Development. In *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1203-1306.

Shindell et al. (2016). Climate and health impacts of US emissions reductions consistent with 2C. *Nature Climate Change* 6: 503-

Shindell, D. (2016). Crop yield changes induced by emissions of individual climate-altering pollutants. *Earth's Future* 4(8): 373–380.

von Stechow et al. (2016). 2 °C and SDGs: united they stand, divided they fall? *Environmental Research Letters* 11:15pp.

von Stechow et al. (2015) Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources* 40:363-394.

2.8 Knowledge gaps

2.9 Cross-cutting boxes [potential ideas]

- Solar radiation management
- Behavioral component (energy efficiency gap)

2.10 Case studies [potential ideas]

- National/regional pathway, or of a globalized sector, or systems like cities/food system, example of jurisdiction committed to carbon neutrality and progress
- SIDS mitigation and adaptation

References

Abrahamse, W., L. Steg, C. Vlek, and T. Rothengatter, 2005: A review of intervention studies aimed at household energy conservation. *J. Environ. Psychol.*, **25**, 273–291.

Agrawala S., S. Klasen, R. Acosta Moreno, L. Barreto, T. Cottier, D. Guan, E. E. Gutierrez-Espeleta, A. E. Gámez Vázquez, L. Jiang, Y. G. Kim, J. Lewis, M. Messouli, M. Rauscher, N. Uddin, and A. V., 2014: Regional Development and Cooperation. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1083–1140.

Allen, M. R., J. S. Fuglestvedt, K. P. Shine, A. Reisinger, R. T. Pierrehumbert, and P. M. Forster, 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Chang.*, **6**, 1–5, doi:10.1038/nclimate2998. http://www.nature.com/doifinder/10.1038/nclimate2998.

Anderson, K., 2015: Talks in the city of light generate more heat. *Nature*, **528**, 437, doi:10.1038/528437a.

Anderson, K., 2015: Duality in climate science. *Nat. Geosci.*, **8**, 898–900, doi:10.1038/ngeo2559.

Anderson, K., and G. Peters, 2016: The trouble with negative emissions. *Science (80-.).*, **354**, 182–183, doi:10.1126/science.aah4567. http://science.sciencemag.org/content/354/6309/182.

Arneth, A., and Coauthors, 2017: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. *Nat. Geosci.*, **10**, 79–84, doi:10.1038/ngeo2882.

Arrow, K., and Coauthors, 2013: Determining Benefits and Costs for Future Generations. *Science (80-.).*, **341**, 349–350, doi:10.1126/science.1235665.

Azar, C., K. Lindgren, M. Obersteiner, K. Riahi, D. P. van Vuuren, K. M. G. J. den Elzen, K. Möllersten, and E. D. Larson, 2010: The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Clim. Change*, **100**, 195–202, doi:10.1007/s10584-010-9832-7.

Ballantyne, A. P., and Coauthors, 2015: Audit of the global carbon budget: estimate errors and their impact on uptake uncertainty. *Biogeosciences*, **12**, 2565–2584.

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, J. Williams, and F. Jotzo, 2016: The need for national deep decarbonization pathways for effective climate policy. *Clim. Policy*, **16**, S7–S26, doi:10.1080/14693062.2016.1173005.

Bauer, N., and Coauthors, 2015: CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. *Technol. Forecast. Soc. Change*, **90**, 243–256, doi:10.1016/j.techfore.2013.09.009. http://dx.doi.org/10.1016/j.techfore.2013.09.009.

Bauer, N., and Coauthors, 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Glob. Environ. Chang.*, **42**, 316–330, doi:10.1016/j.gloenvcha.2016.07.006. http://dx.doi.org/10.1016/j.gloenvcha.2016.07.006.

Bauer, N., I. Mouratiadou, G. Luderer, L. Baumstark, R. J. Brecha, O. Edenhofer, and E. Kriegler, 2016: Global fossil energy markets and climate change mitigation - an analysis with REMIND. *Clim. Change*, **136**, 69–82, doi:10.1007/s10584-013-0901-6.

Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac, and J. Eom, 2015: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change*, **90**, 62–72, doi:10.1016/j.techfore.2013.10.001. http://dx.doi.org/10.1016/j.techfore.2013.10.001.

Bertram, C., G. Luderer, R. C. Pietzcker, E. Schmid, E. Kriegler, and O. Edenhofer, 2015: Complementing carbon prices with technology policies to keep climate targets within reach. *Nat. Clim. Chang.*, **5**, 235–239, doi:10.1038/nclimate2514. http://www.nature.com/doifinder/10.1038/nclimate2514.

Bhore, S., and S. Janardhan, 2016: Paris Agreement on Climate Change: A Booster to Enable Sustainable Global Development and Beyond. *Int. J. Environ. Res. Public Health*, **13**, 1134, doi:10.3390/ijerph13111134. http://www.mdpi.com/1660-4601/13/11/1134 (Accessed April 6, 2017).

Bindoff, N., and Coauthors, 2013: Detection and Attribution of Climate Change: from Global to Regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovenermnetal Panel on Climate Change*, 867–952.

Blanco, G., and Coauthors, 2014: Drivers, Trends and Mitigation. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 351–412.

Blanford, G. J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Clim. Change*, **123**, 383–396, doi:10.1007/s10584-013-0951-9.

Borges, A. V, and Coauthors, 2015: Globally significant greenhouse-gas emissions from African inland waters. *Nat. Geosci.*, **8**, 637–642, doi:10.1038/ngeo2486.

Bosetti, V., G. Marangoni, E. Borgonovo, L. Diaz Anadon, R. Barron, H. C. McJeon, S. Politis, and P. Friley, 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244–263, doi:10.1016/j.enpol.2014.12.012. http://www.sciencedirect.com/science/article/pii/S0301421514006776.

Boucher, O., and Coauthors, 2013: Clouds and Aerosols. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*

Change, 571–657.

Boucher, O., B. de Guillebon, L. Abbadie, P. Barré, S. Bekki, and B. Bensaude-Vincent, 2014: *Atelier de Réflexion Prospective REAGIR - Réflexion systémique sur les enjeux et méthodes de la géo-ingénierie de l'environnement*. Paris, France, 1-89 pp.

Boucher, O., and Coauthors, 2012: Reversibility in an Earth System model in response to CO_2 concentration changes. *Environ. Res. Lett.*, **7**, 24013, doi:10.1088/1748-9326/7/2/024013.

Boucher, O., and Coauthors, 2016: Opinion: In the wake of Paris Agreement, scientists must embrace new directions for climate change research. *Proc. Natl. Acad. Sci.*, **113**, 7287–7290, doi:10.1073/pnas.1607739113.

Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. *Clim. Chang. Econ.*, **5**, 1440005, doi:10.1142/S2010007814400053. http://www.worldscientific.com/doi/abs/10.1142/S2010007814400053.

Bowerman, N. H. A., D. J. Frame, C. Huntingford, J. A. Lowe, and M. R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **369**, 45–66, doi:10.1098/rsta.2010.0288.

Bowerman, N. H. A., D. J. Frame, C. Huntingford, J. A. Lowe, S. M. Smith, and M. R. Allen, 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nat. Clim. Chang.*, **3**, 1021–1024, doi:10.1038/nclimate2034. http://dx.doi.org/10.1038/nclimate2034%5Cnhttp://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2034.html.

Boysen, L. R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations. *Environ. Res. Lett.*, **11**, 1–10, doi:10.1088/1748-9326/11/9/095010.

Bruckner, T., I. A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 511–598.

Calvin, K., and Coauthors, 2017: The SSP4: A world of deepening inequality. *Glob. Environ. Chang.*, **42**, 284–296, doi:10.1016/j.gloenvcha.2016.06.010. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.010.

Calvin, K., M. Wise, P. Kyle, P. Patel, L. Clarke, and J. Edmonds, 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change*, **123**, 691–704, doi:10.1007/s10584-013-0897-y.

Christensen, J. H., and Coauthors, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change Supplementary Material. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 62.

Church, J. a., and Coauthors, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1137–1216.

Ciais, P., and Coauthors, 2013: Carbon and Other Biogeochemical Cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 465–570 http://www.ipcc.ch/report/ar5/wg1/docs/review/WG1AR5_SOD_Ch06_All_Final.pdf%5Cnhttp://ebooks.cambridge.org/ref/id/CBO9781107415324A023.

Clarke, L., and Coauthors, 2014: Assessing Transformation Pathways. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler,*.

Coleman, J., and T. Fararo, 1992: *Rational Choice Theory*. SAGE Publications, Newbury Park,.

Collins, M., and Coauthors, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1029–1136, doi:10.1017/CBO9781107415324.024.

Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Glob. Environ. Chang.*, **42**, 226–236, doi:10.1016/j.gloenvcha.2015.02.012. http://www.sciencedirect.com/science/article/pii/S0959378015000382 (Accessed April 4, 2017).

Creutzig, F., A. Popp, R. Plevin, G. Luderer, J. Minx, and O. Edenhofer, 2012: Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nat. Clim. Chang.*, **2**, 320–327, doi:10.1038/nclimate1416. http://dx.doi.org/10.1038/nclimate1416.

Creutzig, F., and Coauthors, 2015: Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, **7**, 916–944, doi:10.1111/gcbb.12205.

Cubasch, U., D. Wuebbles, D. Chen, M. C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 119–158.

de_Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Prog. Energy Combust. Sci.*, **60**, 68–96, doi:10.1016/j.pecs.2017.01.001. http://linkinghub.elsevier.com/retrieve/pii/S0360128516300569 (Accessed March 18, 2017).

Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared

Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 1–15, doi:10.1016/j.gloenvcha.2015.06.004. http://linkinghub.elsevier.com/retrieve/pii/S0959378015000837.

den Elzen, M. G. J., and D. P. van Vuuren, 2007: Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. *Proc. Natl. Acad. Sci.*, **104**, 17931–17936, doi:10.1073/pnas.0701598104.

Denman, K. L., 2008: Climate change, ocean processes and ocean iron fertilization. *Mar. Ecol. Prog. Ser.*, **364**, 219–225. http://www.int-res.com/abstracts/meps/v364/p219-225/.

Dietz, S., and N. Stern, 2008: Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Rev. Environ. Econ. Policy*, **2**, 94–113, doi:10.1093/reep/ren001.

Dietz, T., G. Gardner, J. Gilligan, P. Stern, and M. Vandenbergh, 2009: Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proc. Natl. Acad. Sci.*, **106**, 18452–18456.

Diffenbaugh, N. S., and A. Charland, 2016: Probability of emergence of novel temperature regimes at different levels of cumulative carbon emissions. *Front. Ecol. Environ.*, **14**, 418–423, doi:10.1002/fee.1320.

Ebi, K. L., and G. Yohe, 2013: Adaptation in first- and second-best worlds. *Curr. Opin. Environ. Sustain.*, **5**, 373–377, doi:10.1016/j.cosust.2013.06.004. http://www.sciencedirect.com/science/article/pii/S1877343513000730 (Accessed March 29, 2017).

Eby, M., A. J. Weaver, K. Alexander, K. Zickfeld, A. Abe-Ouchi, A. A. Cimatoribus, and E. Crespin, 2013: Geoscientific Instrumentation Methods and Data Systems Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity. *Clim. Past*, **9**, 1111–1140, doi:10.5194/cp-9-1111-2013.

Edenhofer, O., and J. Minx, 2014: Mapmakers and navigators, facts and values. *Science (80-.).*, **345**, 37–38, doi:10.1126/science.1255998. http://www.sciencemag.org/cgi/doi/10.1126/science.1255998 (Accessed December 12, 2015).

Edenhofer, O., and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environ. Sci. Policy*, **51**, 56–64, doi:10.1016/j.envsci.2015.03.017. http://www.sciencedirect.com/science/article/pii/S1462901115000660 (Accessed September 11, 2015).

Edenhofer, O., and Coauthors, 2014: Technical Summary. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 33–107.

Edwards, M. R., and J. E. Trancik, 2014: Climate impacts of energy technologies depend on emissions timing. *Nat. Clim. Chang.*, **4**, 347–352, doi:10.1038/nclimate2204. http://www.nature.com/nclimate/journal/v4/n5/full/nclimate2204.html (Accessed June 13, 2016).

Eliseev, A. V., 2012: Climate change mitigation via sulfate injection to the stratosphere: impact on the global carbon cycle and terrestrial biosphere. *Atmos. Ocean. Opt.*, **25**, 405–413, doi:10.1134/S1024856012060024.

Eom, J., J. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and D. P. Van Vuuren, 2015: The impact of near-term climate policy choices on technology and emission transition pathways. *Technol. Forecast. Soc. Change*, **90**, 73–88, doi:10.1016/j.techfore.2013.09.017. http://dx.doi.org/10.1016/j.techfore.2013.09.017.

Etminan, M., G. Myhre, E. J. Highwood, and K. P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.*, **43**, 12,614-12,623, doi:10.1002/2016GL071930. http://doi.wiley.com/10.1002/2016GL071930 (Accessed April 5, 2017).

Faber, J., and Coauthors, 2012: *Behavioural climate change mitigation options and their appropriate inclusion in quantitative longer term policy scenarios*. CE Delft, Fraunhofer ISI, LEI Wageningen, Delft,.

Fawcett, A. A., and Coauthors, 2015: Can Paris pledges avert severe climate change? *Science (80-.).*, **350**, 1168–1169, doi:10.1126/science.aad5761.

Fischedick, M., and Coauthors, 2014: Industry. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 739–810.

Flato, G., and Coauthors, 2013: Evaluation of Climate Models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 741–866.

Fleurbaey, M., and Coauthors, 2014: Sustainable Development and Equity. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Fricko, O., and Coauthors, 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.*, **42**, 251–267, doi:10.1016/j.gloenvcha.2016.06.004. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004.

Fricko, O., S. C. Parkinson, N. Johnson, M. Strubegger, M. T. van Vliet, and K. Riahi, 2016: Energy sector water use implications of a 2 °C climate policy. *Environ. Res. Lett.*, **11**, 34011, doi:10.1088/1748-9326/11/3/034011.

Friedlingstein, P., and Coauthors, 2014: Persistent growth of CO2 emissions and implications for reaching climate targets. *Nat. Geosci.*, **7**, 709–715, doi:10.1038/ngeo2248. http://www.nature.com/doifinder/10.1038/ngeo2248 (Accessed April 4, 2017).

Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti, 2013:

Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks. *J. Clim.*, **27**, 511–526, doi:10.1175/JCLI-D-12-00579.1.

Frölicher, T. L., 2016: Climate response: Strong warming at high emissions. *Nat. Clim. Chang.*, **6**, 823–824, doi:10.1038/nclimate3053.

Frölicher, T. L., and D. J. Paynter, 2015: Is the climate response to carbon emissions path dependent? *Geophys. Res. Lett.*, **39**, L05703, doi:10.1088/1748-9326/10/7/075002. http://iopscience.iop.org/article/10.1088/1748-9326/10/7/075002 (Accessed April 4, 2017).

Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 268–283, doi:10.1016/j.gloenvcha.2016.06.009. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009.

Fujimori, S., X. Su, J.-Y. Liu, T. Hasegawa, K. Takahashi, T. Masui, and M. Takimi, 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *Springerplus*, **5**, 1620, doi:10.1186/s40064-016-3235-9. http://www.ncbi.nlm.nih.gov/pubmed/27652193 (Accessed April 6, 2017).

Fuss, S., and Coauthors, 2014: Betting on negative emissions. *Nat. Clim. Chang.*, **4**, 850–853, doi:10.1038/nclimate2392.

Gasser, T., C. Guivarch, K. Tachiiri, C. D. Jones, and P. Ciais, 2015: Negative emissions physically needed to keep global warming below 2 °C. *Nat. Commun.*, **6**, 7958, doi:10.1038/ncomms8958. http://www.nature.com/ncomms/2015/150803/ncomms8958/full/ncomms8958.html.

Geels, F. W., F. Berkhout, and D. P. van Vuuren, 2016: Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Chang.*, **advance on**, 576–583, doi:10.1038/nclimate2980. http://dx.doi.org/10.1038/nclimate2980.

Geoffroy, O., D. Saint-Martin, and A. Voldoire, 2015: Land-sea warming contrast: the role of the horizontal energy transport. *Clim. Dyn.*, **45**, 3493–3511, doi:10.1007/s00382-015-2552-y.

Gernaat, D. E. H. J., K. Calvin, P. L. Lucas, G. Luderer, S. A. C. Otto, S. Rao, J. Strefler, and D. P. van Vuuren, 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Glob. Environ. Chang.*, **33**, 142–153, doi:10.1016/j.gloenvcha.2015.04.010. http://dx.doi.org/10.1016/j.gloenvcha.2015.04.010.

Gillett, N. P., V. K. Arora, D. Matthews, and M. R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. *J. Clim.*, **26**, 6844–6858, doi:10.1175/JCLI-D-12-00476.s1.

Gillett, N. P., and H. D. Matthews, 2010: Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. *Environ. Res. Lett.*, **5**, 34011, doi:10.1088/1748-9326/5/3/034011.

Goode, W. J., 1997: Rational choice theory. *Am. Sociol.*, **28**, 22–41.

Goodwin, P., R. G. Williams, and A. Ridgwell, 2014: Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake. *Nat. Geosci.*, **8**, 29–34, doi:10.1038/ngeo2304.

Gregory, J. M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophys. Res. Lett.*, **43**, 3911–3920, doi:10.1002/2016GL068406. http://doi.wiley.com/10.1002/2016GL068406 (Accessed April 5, 2017).

Griggs, D., and Coauthors, 2014: An integrated framework for sustainable development goals. *Ecol. Soc.*, **19**, doi:10.5751/ES-07082-190449.

Gupta, S., and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Inter- Gov. Panel Clim. Chang.*, 1207–1246, doi:10.1017/CBO9781107415416.022.

Hallegatte, S., and Coauthors, 2016: Mapping the climate change challenge. *Nat. Clim. Chang.*, **6**, 663–668, doi:10.1038/nclimate3057. http://dx.doi.org/10.1038/nclimate3057%5Cnhttp://www.nature.com/doifinder/10.1038/nclimate3057.

Hartmann, D. J., and Coauthors, 2013: Observations: Atmosphere and Surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 159–254 http://www.climatechange2013.org/report/full-report/.

Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr, and J. Scheffran, 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.*, **51**, 113–149, doi:10.1002/rog.20004. http://onlinelibrary.wiley.com/doi/10.1002/rog.20004/abstract (Accessed January 6, 2014).

Hauck, J., P. Köhler, D. Wolf-Gladrow, and C. Völker, 2016: Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO2 removal experiment. *Environ. Res. Lett.*, **11**, 24007–24011, doi:10.1088/1748-9326/11/2/024007.

Heck, V., J. F. Donges, and W. Lucht, 2016: Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal. *Earth Syst. Dyn.*, **7**, 783–796, doi:10.5194/esd-7-783-2016.

Heck, V., D. Gerten, W. Lucht, and L. R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a “green” form of geoengineering? A global modelling study. *Glob. Planet. Change*, **137**, 123–130, doi:10.1016/j.gloplacha.2015.12.008.

Hermoso, V., 2017: Freshwater ecosystems could become the biggest losers of the Paris Agreement. *Glob. Chang. Biol.*, doi:10.1111/gcb.13655. http://doi.wiley.com/10.1111/gcb.13655.

Hermwille, L., W. Obergassel, H. E. Ott, and C. Beuermann, 2015: UNFCCC before and after Paris – what's necessary for an effective climate regime? *Clim. Policy*, **3062**, 1–21, doi:10.1080/14693062.2015.1115231. http://dx.doi.org/10.1080/14693062.2015.1115231.

Hof, A. F., M. G. J. den Elzen, A. Admiraal, M. Roelfsema, D. E. H. J. Gernaat, and D. P. van Vuuren, 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. *Environ. Sci. Policy*, **71**, 30–40, doi:10.1016/j.envsci.2017.02.008. http://www.sciencedirect.com/science/article/pii/S1462901116308978 (Accessed April 6, 2017).

Humpenöder, F., and Coauthors, 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.*, **9**, 64029, doi:10.1088/1748-9326/9/6/064029. http://iopscience.iop.org/1748-9326/9/6/064029 (Accessed June 24, 2014).

Huntingford, C., and J. Lowe, 2007: Overshoot scenarios and climate change. *Science (80-.).*, **316**, 829, doi:10.1126/science.316.5826.829b.

Huntingford, C., J. A. Lowe, L. K. Gohar, N. H. A. Bowerman, M. R. Allen, S. C. B. Raper, and S. M. Smith, 2012: The link between a global 2 °C warming threshold and emissions in years 2020, 2050 and beyond. *Environ. Res. Lett.*, **7**, 14039, doi:10.1088/1748-9326/7/1/014039.

IEA, 2016: *World Energy Investment 2016*. IEA/OECD, Paris,.

Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO2 and ocean acidification. *Geophys. Res. Lett.*, **40**, 5909–5914, doi:10.1002/2013GL057981.

IPCC, 2014: Summary for Policymakers - Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambirdge University Press, Cambridge, UK, and New York, NY, USA, 1–30.

IPCC, 2014: Climate Change 2014 Synthesis Report Summary - Chapter for Policymakers. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 31.

IPCC, 2014: Climate Change 2014 Synthesis Report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1–112.

Iyer, G. C., L. E. Clarke, J. A. Edmonds, B. P. Flannery, N. E. Hultman, H. C. McJeon, and D. G. Victor, 2015: Improved representation of investment decisions in assessments of CO2 mitigation. *Nat. Clim. Chang.*, **5**, 436–440, doi:10.1038/nclimate2553. http://www.nature.com/nclimate/journal/v5/n5/full/nclimate2553.html (Accessed April 23, 2015).

Iyer, G. C., and Coauthors, 2015: The contribution of Paris to limit global warming to 2 °C. *Environ. Res. Lett.*, **10**, 125002, doi:10.1088/1748-9326/10/12/125002. http://stacks.iop.org/1748-9326/10/i=12/a=125002.

Jackson, R. B., and Coauthors, 2008: Protecting climate with forests. *Environ. Res. Lett.*, **3**, 44006, doi:10.1088/1748-9326/3/4/044006.

Jakob, M., and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.*, **11**, 104010, doi:10.1088/1748-9326/11/10/104010. http://stacks.iop.org/1748-9326/11/i=10/a=104010?key=crossref.4cd77602bc9540b790e45408383c5286 (Accessed April 5, 2017).

Jewell, J., and Coauthors, 2016: Comparison and interactions between the long-term pursuit of energy independence and climate policies. *Nat. Energy*, **1**, 16073, doi:10.1038/nenergy.2016.73. http://www.nature.com/articles/nenergy201673 (Accessed June 8, 2016).

Jiang, L., and B. C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 193–199, doi:10.1016/j.gloenvcha.2015.03.008. http://www.sciencedirect.com/science/article/pii/S0959378015000394 (Accessed April 4, 2017).

Johannessen, S. C., and R. W. Macdonald, 2016: Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.*, **11**, 113001, doi:10.1088/1748-9326/11/11/113001.

Johnson, N., V. Krey, D. L. McCollum, S. Rao, K. Riahi, and J. Rogelj, 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change*, **90**, 89–102, doi:10.1016/j.techfore.2014.02.028. http://www.sciencedirect.com/science/article/pii/S0040162514000924 (Accessed April 5, 2017).

Jones, C. D., and Coauthors, 2016: Simulating the Earth system response to negative emissions. *Environ. Res. Lett.*, **11**, 95012, doi:10.1088/1748-9326/11/9/095012.

Jones, C., and Coauthors, 2013: Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. *J. Clim.*, **26**, 4398–4413, doi:10.1175/JCLI-D-12-00554.1.

Joos, F., and Coauthors, 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos. Chem. Phys.*, **13**, 2793–2825, doi:10.5194/acp-13-2793-2013.

Karen C., S., and Coauthors, 2014: Human Settlements, Infrastructure, and Spatial Planning. *Climate Change 2014:*

Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 923–1000.

KC, S., and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004. http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Keith, D. W., M. Ha-Duong, and J. K. Stolaroff, 2006: Climate Strategy with CO2 Capture from the Air. *Clim. Change*, **74**, 17–45, doi:10.1007/s10584-005-9026-x. http://link.springer.com/10.1007/s10584-005-9026-x (Accessed April 16, 2015).

Keith, D. W., and J. S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Clim. Change*, **54**, 375–377. http://dx.doi.org/10.1023/A:1016187420442.

Kheshgi, H. S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20**, 915–922, doi:10.1016/0360-5442(95)00035-F. http://linkinghub.elsevier.com/retrieve/pii/036054429500035F (Accessed April 1, 2017).

Kirtman, B., A. Adedoyin, and N. Bindoff, 2013: Near-term Climate Change: Projections and Predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 953–1028 ftp://halo.ess.uci.edu/Public/prather/paper_N2O/IPCC WGI AR5 Ch 11 v30.doc.

Klein, D., and Coauthors, 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Clim. Change*, **123**, 705–718, doi:10.1007/s10584-013-0940-z.

Knutti, R., J. Rogelj, J. Sedláček, and E. M. Fischer, 2015: A scientific critique of the two-degree climate change target. *Nat. Geosci.*, **9**, 13–18, doi:10.1038/ngeo2595.

Kolstad, C., and Coauthors, 2014: Social, Economic and Ethical Concepts and Methods. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Krasting, J. P., J. P. Dunne, E. Shevliakova, and R. J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophys. Res. Lett.*, **41**, 2520–2527, doi:10.1002/(ISSN)1944-8007.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Clim. Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.

Krey, V., and Coauthors, 2014: Annex II: Metrics & Methodology. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1281–1328.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change*, **118**, doi:10.1007/s10584-012-0681-4.

Kriegler, E., and Coauthors, 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change*, **123**, doi:10.1007/s10584-013-0953-7.

Kriegler, E., and Coauthors, 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Chang.*, **42**, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.

Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Clim. Change*, **122**, 401–414, doi:10.1007/s10584-013-0971-5.

Kriegler, E., and Coauthors, 2015: Diagnostic indicators for integrated assessment models of climate policy. *Technol. Forecast. Soc. Change*, **90**, 45–61, doi:10.1016/j.techfore.2013.09.020. http://dx.doi.org/10.1016/j.techfore.2013.09.020.

Kriegler, E., and Coauthors, 2015: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change*, **90**, **Part A**, 24–44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E., and Coauthors, 2013: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios. *Clim. Chang. Econ.*, **4**, 1340008, doi:10.1142/S2010007813400083. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400083.

Kunreuther, H., and Coauthors, 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

L., C., and Coauthors, 2014: Assessing Transformation Pathways: Section 6.3. *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report*, Intergovernmental Panel on Climate Change, Ed., Cambridge University Press, Cambridge https://www.cambridge.org/core/books/climate-change-2014-mitigation-of-climate-change/assessing-transformation-pathways/D642274A45199DE83B0C8C2EB763BBA4.

Lackner, K. S., S. Brennan, J. M. Matter, A.-H. A. Park, A. Wright, and B. Van Der Zwaan, 2012: The urgency of the development of CO2 capture from ambient air. *Proc. Natl. Acad. Sci.*, **109**, 13156–13162.

http://www.pnas.org/content/109/33/13156.short (Accessed April 21, 2015).

Lal, R., 2004: Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science (80-.).*, **304**, 1623 LP-1627. http://science.sciencemag.org/content/304/5677/1623.abstract.

Le Page, Y., and Coauthors, 2013: Sensitivity of climate mitigation strategies to natural disturbances. *Environ. Res. Lett.*, **8**, 15018, doi:10.1088/1748-9326/8/1/015018.

Le Quéré, C., and Coauthors, 2016: Global Carbon Budget 2016. *ESSD*, **8**, 605–649, doi:10.5194/essd-8-605-2016.

Leduc, M., H. D. Matthews, and R. de Elía, 2016: Regional estimates of the transient climate response to cumulative CO2 emissions. *Nat. Clim. Chang.*, **6**, 474, doi:10.1038/nclimate2913. http://www.nature.com/doifinder/10.1038/nclimate2913 (Accessed April 5, 2017).

Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions – A GDP scenario approach. *Glob. Environ. Chang.*, **42**, 215–225, doi:10.1016/j.gloenvcha.2015.02.005. http://www.sciencedirect.com/science/article/pii/S0959378015000242 (Accessed April 4, 2017).

Lowe, J. A., C. Huntingford, S. C. B. Raper, C. D. Jones, S. K. Liddicoat, and L. K. Gohar, 2009: How difficult is it to recover from dangerous levels of global warming? *Environ. Res. Lett.*, **4**, 14012, doi:10.1088/1748-9326/4/1/014012.

Lucon, O., and Coauthors, 2014: Buildings. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 671–738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Clim. Change*, **136**, 127–140, doi:10.1007/s10584-013-0899-9.

Luderer, G., R. C. Pietzcker, C. Bertram, E. Kriegler, and M. Meinshausen, 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033, doi:10.1088/1748-9326/8/3/034033.

MacDougall, A. H., and P. Friedlingstein, 2015: The Origin and Limits of the Near Proportionality between Climate Warming and Cumulative CO 2 Emissions. *J. Clim.*, **28**, 4217–4230, doi:10.1175/JCLI-D-14-00036.1. http://journals.ametsoc.org/doi/10.1175/JCLI-D-14-00036.1 (Accessed April 4, 2017).

MacMartin, D. G., B. Kravitz, J. C. S. Long, and P. J. Rasch, 2016: Geoengineering with stratospheric aerosols: What do we not know after a decade of research? *Earth's Futur.*, **4**, 543–548, doi:10.1002/2016EF000418.

Marangoni, G., and Coauthors, 2017: Sensitivity of projected long-term CO2 emissions across the Shared Socioeconomic Pathways. *Nat. Clim. Chang.*, **7**, 6–8, doi:10.1038/nclimate3199. http://www.nature.com/doifinder/10.1038/nclimate3199.

Marland, G., and Coauthors, 2003: The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Clim. Policy*, **3**, 149–157, doi:10.1016/S1469-3062(03)00028-7. http://www.sciencedirect.com/science/article/pii/S1469306203000287 (Accessed April 1, 2017).

Masson-Delmotte, V., and Coauthors, 2013: Information from Paleoclimate Archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 383–464.

Mathiesen, B. V., and K. Karlsson, 2011: 100% Renewable energy systems, climate mitigation and economic growth. *Appl. Energy*, **88**, 488–501, doi:10.1016/j.apenergy.2010.03.001. http://www.sciencedirect.com/science/article/pii/S0306261910000644 (Accessed April 1, 2017).

Matthews, H. D., and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, **35**, 1–5, doi:10.1029/2007GL032388.

Matthews, H. D., N. P. Gillett, P. A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459**, 829–832, doi:10.1038/nature08047.

Matthews, H. D., J.-S. Landry, A.-I. Partanen, M. Allen, M. Eby, P. M. Forster, P. Friedlingstein, and K. Zickfeld, 2017: Estimating Carbon Budgets for Ambitious Climate Targets. *Curr. Clim. Chang. Reports*, 69–77, doi:10.1007/s40641-017-0055-0. http://link.springer.com/10.1007/s40641-017-0055-0.

Mazzotti, M., and Coauthors, 2005: Mineral carbonation and industrial uses of carbon dioxide. *IPCC Spec. Rep. Carbon dioxide Capture Storage*, 319–338. http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter7.pdf.

McCollum, D. L., Y. Nagai, K. Riahi, G. Marangoni, K. Calvin, R. Pietzcker, J. van Vliet, and B. van der Zwaan, 2013: Energy Investments Under Climate Policy: a Comparison of Global Models. *Clim. Chang. Econ.*, **4**, doi:10.1142/s2010007813400101.

McCollum, D. L., and Coauthors, 2016: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transp. Res. Part D Transp. Environ.*, doi:10.1016/j.trd.2016.04.003. http://www.sciencedirect.com/science/article/pii/S1361920915300900 (Accessed April 4, 2017).

McCollum, D. L., V. Krey, and K. Riahi, 2011: An integrated approach to energy sustainability. *Nat. Clim. Chang.*, **1**, 428–429, doi:10.1038/nclimate1297. http://www.nature.com/nclimate/journal/v1/n9/full/nclimate1297.html (Accessed January 29, 2014).

McCollum, D., N. Bauer, K. Calvin, A. Kitous, and K. Riahi, 2014: Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Clim. Change*, **123**, 413–426, doi:10.1007/s10584-013-0939-5.

Mcleod, E., and Coauthors, 2011: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front. Ecol. Environ.*, **9**, 552–560, doi:10.1890/110004.

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley, 2011: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.*, **11**, 1417–1456, doi:10.5194/acp-11-1417-2011.

Mercado, L. M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P. M. Cox, 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458**, 1014–1017, doi:10.1038/nature07949.

Moore, F. C., and D. B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nat. Clim. Chang.*, **5**, 127–131, doi:10.1038/nclimate2481.

Moss, R. H., and Coauthors, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756, doi:10.1038/nature08823. http://www.nature.com/nature/journal/v463/n7282/abs/nature08823.html (Accessed December 2, 2014).

Mundaca, L., L. Neij, A. Markandya, P. Hennicke, and J. Yan, 2016: Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways. *Appl. Energy*, **179**, 1283–1292.

Mundaca, L., and A. Markandya, 2016: Assessing regional progress towards a “Green Energy Economy.” *Appl. Energy*, **179**, 1372–1394, doi:10.1016/j.apenergy.2015.10.098.

Myhre, G., and Coauthors, 2013: Anthropogenic and Natural Radiative Forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 659–740.

Nakicenovic, N., and Coauthors, 2000: *IPCC Special Report on Emissions Scenarios*. Nebojsa Nakicenovic and Rob Swart, Eds. Cambridge University Press, Cambridge, 570 pp. http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0 (Accessed April 4, 2017).

Nilsson, S., and W. Schopfhauser, 1995: The carbon-sequestration potential of a global afforestation program. *Clim. Change*, **30**, 267–293, doi:10.1007/BF01091928. http://dx.doi.org/10.1007/BF01091928.

Nohara, D., J. Tsutsui, S. Watanabe, K. Tachiiri, T. Hajima, H. Okajima, and T. Matsuno, 2015: Examination of a climate stabilization pathway via zero-emissions using Earth system models. *Environ. Res. Lett.*, **10**, 95005, doi:10.1088/1748-9326/10/9/095005. http://stacks.iop.org/1748-9326/10/i=9/a=095005?key=crossref.4e5e0374e7c14332fa54ac1533086f06 (Accessed April 5, 2017).

Nordhaus, W., 2007: A Review of the “Stern Review on the Economics of Climate Change.” *J. Econ. Lit.*, 686–702.

Nordhaus, W. D., 2013: *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press, 392 pp.

Obersteiner, M., and Coauthors, 2001: Managing Climate Risk. *Science (80-.).*, **294**, 786–787.

O’Neill, B. C., and Coauthors, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004. http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

O’Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim. Change*, **122**, 387–400, doi:10.1007/s10584-013-0905-2.

Otto, A., and Coauthors, 2013: Energy budget constraints on climate response. *Nat. Geosci*, **6**, 415–416. http://dx.doi.org/10.1038/ngeo1836.

Otto, F. E. L., D. J. Frame, A. Otto, and M. R. Allen, 2015: Embracing uncertainty in climate change policy. *Nat. Clim. Chang.*, **5**, 917–920, doi:10.1038/nclimate2716. http://www.nature.com/doifinder/10.1038/nclimate2716 (Accessed April 5, 2017).

Paltsev, S., and P. Capros, 2013: Cost Concepts for Climate Change Mitigation. *Clim. Chang. Econ.*, **4**, 1340003, doi:10.1142/S2010007813400034. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400034.

Pendleton, L., and Coauthors, 2012: Estimating Global “Blue Carbon” Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. *PLoS One*, **7**, e43542-7, doi:10.1371/journal.pone.0043542.

Peters, G. P., 2016: The “best available science” to inform 1.5 °C policy choices. *Nat. Clim. Chang.*, **6**, 646–649, doi:10.1038/nclimate3000.

Peters, G. P., and Coauthors, 2013: The challenge to keep global warming below 2 °C. *Nat. Clim. Chang.*, **3**, 4–6, doi:10.1038/nclimate1783.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The “2°C capital stock” for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Appl. Energy*, **179**, 1395–1408, doi:10.1016/j.apenergy.2016.02.093.

Pietzcker, R. C., T. Longden, W. Chen, S. Fu, E. Kriegler, P. Kyle, and G. Luderer, 2014: Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy*, **64**, 95–108, doi:10.1016/j.energy.2013.08.059.

Pietzcker, R. C., and Coauthors, 2016: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Econ.*, doi:10.1016/j.eneco.2016.11.018. http://www.sciencedirect.com/science/article/pii/S0140988316303395 (Accessed April 4, 2017).

Popp, A., and Coauthors, 2017: Land-use futures in the shared socio-economic pathways. *Glob. Environ. Chang.*, **42**,

doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.10.002. http://www.sciencedirect.com/science/article/pii/S0959378016303399.
Popp, A., and Coauthors, 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Clim. Change*, **123**, 495–509, doi:10.1007/s10584-013-0926-x.
Ranjan, R., 2014: Optimal carbon mitigation strategy under non-linear feedback effects and in the presence of permafrost release trigger hazard. *Mitig. Adapt. Strateg. Glob. Chang.*, **19**, 479–497, doi:10.1007/s11027-012-9444-9.
Rao, S., and Coauthors, 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environ. Res. Lett.*, **11**, 124013, doi:10.1088/1748-9326/11/12/124013. http://stacks.iop.org/1748-9326/11/i=12/a=124013?key=crossref.b4de2f0ebe431be6d994766c93883b95.
Rao, S., and Coauthors, 2017: Future air pollution in the Shared Socio-economic Pathways. *Glob. Environ. Chang.*, **42**, 346–358, doi:10.1016/j.gloenvcha.2016.05.012.
Raupach, M. R., and Coauthors, 2014: Sharing a quota on cumulative carbon emissions. *Nat. Clim. Chang.*, **4**, 873–879, doi:10.1038/nclimate2384. http://www.nature.com/doifinder/10.1038/nclimate2384 (Accessed April 5, 2017).
Regnier, P., and Coauthors, 2013: Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nat. Geosci.*, **6**, 597–607, doi:10.1038/ngeo1830.
Revesz, R., P. Howard, K. Arrow, L. Goulder, R. Kopp, M. Livermore, M. Oppenheimer, and T. Sterner, 2014: Global warming: Improve economic models of climate change. *Nature*, **508**, 173–175.
Rhein, Monika; Rintoul, S. R., 2013: Observations: Ocean. *Climate Change 2013 - The Physical Science Basis*, 255–316 http://dx.doi.org/10.1017/CBO9781107415324.010.
Riahi, K., and Coauthors, 2012: Chapter 17 - Energy Pathways for Sustainable Development. *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 1203–1306.
Riahi, K., and Coauthors, 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change*, **90**, 8–23, doi:10.1016/j.techfore.2013.09.016. http://dx.doi.org/10.1016/j.techfore.2013.09.016.
Riahi, K., and Coauthors, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.
Rockström, B. J., O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H. Joachim, 2017: A roadmap for rapid decarbonization. **355**, doi:10.1126/science.aah3443.
Rockström, J., and Coauthors, 2016: The world's biggest gamble. *Earth's Futur.*, **4**, 465–470, doi:10.1002/2016EF000392.
Rogelj, J., and Coauthors, 2016: Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, **534**, 631–639, doi:10.1038/nature18307. http://0-www.nature.com.wam.city.ac.uk/nature/journal/v534/n7609/pdf/nature18307.pdf.
Rogelj, J., and Coauthors, 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Chang.*, **1**, 413–418, doi:10.1038/nclimate1258.
Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi, 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.*, **5**, 519–527, doi:10.1038/nclimate2572. http://www.nature.com/doifinder/10.1038/nclimate2572.
Rogelj, J., D. L. McCollum, and K. Riahi, 2013: The UN's "Sustainable Energy for All" initiative is compatible with a warming limit of 2 °C. *Nat. Clim. Chang.*, **3**, 545, doi:10.1038/nclimate1806. http://www.nature.com/doifinder/10.1038/nclimate1806 (Accessed April 5, 2017).
Rogelj, J., D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature*, **493**, 79–83, doi:10.1038/nature11787. http://www.nature.com/nature/journal/v493/n7430/full/nature11787.html (Accessed December 3, 2014).
Rogelj, J., M. Meinshausen, and R. Knutti, 2012: Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nat. Clim. Chang.*, **2**, 248–253, doi:10.1038/nclimate1385.
Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and R. Keywan, 2015: Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. *Environ. Res. Lett.*, **10**, 75001, doi:10.1088/1748-9326/10/7/075001. http://stacks.iop.org/1748-9326/10/i=7/a=075001.
Rogelj, J., M. Meinshausen, J. Sedláček, and R. Knutti, 2014: Implications of potentially lower climate sensitivity on climate projections and policy. *Environ. Res. Lett.*, **9**, 31003, doi:10.1088/1748-9326/9/3/031003.
Rogelj, J., M. Schaeffer, P. Friedlingstein, N. P. Gillett, D. P. van Vuuren, K. Riahi, M. Allen, and R. Knutti, 2016: Differences between carbon budget estimates unravelled. *Nat. Clim. Chang.*, **6**, 245–252, doi:10.1038/nclimate2868. http://www.nature.com/doifinder/10.1038/nclimate2868.
Rogelj, J., M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare, 2015: Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.*, **10**, 105007, doi:10.1088/1748-9326/10/10/105007. http://stacks.iop.org/1748-9326/10/i=10/a=105007.

Rose, S. K., R. Richels, G. Blanford, and T. Rutherford, 2017: The Paris Agreement and next steps in limiting global warming. *Clim. Change*, 1–16, doi:10.1007/s10584-017-1935-y. http://link.springer.com/10.1007/s10584-017-1935-y (Accessed April 6, 2017).

Rose, S. K., R. Richels, S. Smith, K. Riahi, J. Strefler, and D. P. van Vuuren, 2014: Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Clim. Change*, **123**, 511–525, doi:10.1007/s10584-013-0955-5.

Rose, S. K., E. Kriegler, R. Bibas, K. Calvin, A. Popp, D. P. van Vuuren, and J. Weyant, 2013: Bioenergy in energy transformation and climate management. *Clim. Change*, **123**, 477–493, doi:10.1007/s10584-013-0965-3. http://link.springer.com/article/10.1007/s10584-013-0965-3 (Accessed February 8, 2016).

Sanderson, B. M., B. C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophys. Res. Lett.*, **43**, 7133–7142, doi:10.1002/2016GL069563. http://doi.wiley.com/10.1002/2016GL069563 (Accessed April 6, 2017).

Sanford, T., P. C. Frumhoff, A. Luers, and J. Gulledge, 2014: The climate policy narrative for a dangerously warming world. *Nat. Clim. Chang.*, **4**, 164–166, doi:10.1038/nclimate2148.

Saunois, M., and Coauthors, 2016: The global methane budget 2000–2012. *ESSD*, **8**, 697–751, doi:10.5194/essd-8-697-2016.

Schaeffer, M., L. Gohar, E. Kriegler, J. Lowe, K. Riahi, and D. van Vuuren, 2015: Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technol. Forecast. Soc. Change*, **90**, 257–268, doi:10.1016/j.techfore.2013.09.013. http://dx.doi.org/10.1016/j.techfore.2013.09.013.

Schäfer, A. W., A. D. Evans, T. G. Reynolds, and L. Dray, 2016: Costs of mitigating CO2 emissions from passenger aircraft. *Nat. Clim. Chang.*, **6**, 412–417, doi:10.1038/nclimate2865. http://www.nature.com/nclimate/journal/v6/n4/full/nclimate2865.html (Accessed March 24, 2016).

Schleussner, C.-F., and Coauthors, 2016: Differential climate impacts for policy relevant limits to global warming: the case of 1.5°C and 2°C. *Earth Syst. Dyn.*, **7**, 327–351, doi:10.5194/esd-7-327-2016.

Schleussner, C.-F., and Coauthors, 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Chang.*, **6**, 827–835, doi:10.1038/nclimate3096. http://www.nature.com/nclimate/journal/v6/n9/full/nclimate3096.html.

Schlomer, S., and Coauthors, 2014: Annex III: Technology-specific cost and performance parameters. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1329–1356.

Schneider, T., J. Teixeira, C. S. Bretherton, F. Brient, K. G. Pressel, C. Schär, and A. P. Siebesma, 2017: Climate goals and computing the future of clouds. *Nat. Clim. Chang.*, **7**, 3–5, doi:10.1038/nclimate3190.

Schwalm, C. R., and Coauthors, 2015: Toward "optimal" integration of terrestrial biosphere models. *Geophys. Res. Lett.*, **42**, 4418–4428, doi:10.1002/2015GL064002.

Seto, K. C., S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh, and D. Ürge-Vorsatz, 2016: Carbon lock-in: Types, causes, and policy implications. *Annu. Rev. Environ. Resour.*, **41**, 425–452.

Sherwood, S. C., S. Bony, and J.-L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505**, 37–42. http://dx.doi.org/10.1038/nature12829.

Shindell, D. T., 2014: Inhomogeneous forcing and transient climate sensitivity. *Nat. Clim. Chang.*, **4**, 18–21, doi:10.1038/NCLIMATE2136.

Shindell, D. T., 2016: Crop yield changes induced by emissions of individual climate-altering pollutants. *Earth's Futur.*, **4**, 373–380.

Shindell, D. T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2C. *Nat. Clim. Chang.*, **6**, 503–509.

Shortridge, J. E., and S. D. Guikema, 2016: Scenario Discovery with Multiple Criteria: An Evaluation of the Robust Decision-Making Framework for Climate Change Adaptation. *Risk Anal.*, **36**, 2298–2312, doi:10.1111/risa.12582. http://doi.wiley.com/10.1111/risa.12582 (Accessed March 22, 2017).

Sims, Ralph; Schaeffer, R. et al., 2014: *Transport*.

Smith, P., and Coauthors, 2016: Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.*, **6**, doi:10.1038/nclimate2870.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Glob. Chang. Biol.*, **22**, 1315–1324, doi:10.1111/gcb.13178. http://onlinelibrary.wiley.com/doi/10.1111/gcb.13178/abstract (Accessed August 15, 2016).

Smith, P., and M. et al. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 811–922.

Smith, S. M., J. A. Lowe, N. H. A. Bowerman, L. K. Gohar, C. Huntingford, and M. R. Allen, 2012: Equivalence of greenhouse-gas emissions for peak temperature limits. *Nat. Clim. Chang.*, **2**, 535–538, doi:10.1038/nclimate1496. http://www.nature.com/nclimate/journal/v2/n7/full/nclimate1496.html.

Somanthan, E., and Coauthors, 2014: National and Sub-national Policies and Institutions. *Climate Change 2014:*

Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1141–1206.

Stavins, R., and Coauthors, 2014: International Cooperation: Agreements and Instruments. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Stechow, C. von, and Coauthors, 2016: 2 °C and SDGs: united they stand, divided they fall? *Environ. Res. Lett.*, **11**, 34022, doi:10.1088/1748-9326/11/3/034022.

Steinacher, M., and F. Joos, 2016: Transient Earth system responses to cumulative carbon dioxide emissions: linearities, uncertainties, and probabilities in an observation-constrained model ensemble. *Biogeosciences*, **13**, 1071–1103, doi:10.5194/bg-13-1071-2016.

Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407–409, doi:10.1038/530407a.

Stern, P., K. Janda, M. Brown, L. Steg, E. Vine, and L. Lutzenhiser, 2016: Opportunities and insights for reducing fossil fuel consumption by households and organizations. *Nat. Energy*, **1**, 16043.

Stocker T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. B. and P. M. M. (eds. ., 2013: Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 3–30.

Stocker, T. F., and Coauthors, 2013: Technical Summary. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 33–115.

Tan, I., T. Storelvmo, and M. D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science (80-.).*, **352**. http://science.sciencemag.org/content/352/6282/224 (Accessed April 5, 2017).

Tanaka, K., B. C. O'Neill, D. Rokityanskiy, M. Obersteiner, and R. S. J. Tol, 2009: Evaluating global warming potentials with historical temperature. *Clim. Change*, **96**, 443–466, doi:10.1007/s10584-009-9566-6.

Tavoni, M., and Coauthors, 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nat. Clim. Chang.*, **5**, doi:10.1038/nclimate2475.

Tavoni, M., E. Kriegler, T. Aboumahboub, K. Calvin, G. De Maere, and M. Wise, 2013: The Distribution of the Major Economies' Effort in the Durban Platform Scenarios. *Clim. Chang. Econ.*, **4**, 1–25, doi:10.1142/S2010007814920018.

Tavoni, M., and R. S. J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Clim. Change*, **100**, 769–778, doi:10.1007/s10584-010-9867-9.

Tebaldi, C., and R. Knutti, 2007: The use of the multi-model ensemble in probabilistic climate projections. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **365**, 2053–2075, doi:10.1098/rsta.2007.2076.

The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. 1-5 pp.

Tilmes, S., B. M. Sanderson, and B. C. O'Neill, 2016: Climate impacts of geoengineering in a delayed mitigation scenario. *Geophys. Res. Lett.*, **43**, 8222–8229, doi:10.1002/2016GL070122.

Tokarska, K. B., N. P. Gillett, A. J. Weaver, V. K. Arora, and M. Eby, 2016: The climate response to five trillion tonnes of carbon. *Nat. Clim. Chang.*, **6**, 851–855, doi:10.1038/nclimate3036.

Tokarska, K. B., and K. Zickfeld, 2015: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environ. Res. Lett.*, **10**, 1–11, doi:10.1088/1748-9326/10/9/094013.

van der Zwaan, B. C. C., H. Rösler, T. Kober, T. Aboumahboub, K. V. Calvin, D. E. H. J. Gernaat, G. MARANGONI, and D. McCOLLUM, 2013: A Cross-Model Comparison of Global Long-Term Technology Diffusion Under a 2°C Climate Change Control Target. *Clim. Chang. Econ.*, **4**, 1340013, doi:10.1142/S2010007813400137. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400137.

van Vuuren, D. P., and Coauthors, 2011: The representative concentration pathways: An overview. *Clim. Change*, **109**, 5–31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D. P., and Coauthors, 2011: How well do integrated assessment models simulate climate change? *Clim. Change*, **104**, 255–285, doi:10.1007/s10584-009-9764-2.

van Vuuren, D. P., and Coauthors, 2011: RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Clim. Change*, **109**, 95–116, doi:10.1007/s10584-011-0152-3. http://link.springer.com/10.1007/s10584-011-0152-3 (Accessed April 6, 2017).

van Vuuren, D. P., and Coauthors, 2017: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Chang.*, **42**, 237–250, doi:10.1016/j.gloenvcha.2016.05.008. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.008.

Vandyck, T., K. Keramidas, B. Saveyn, A. Kitous, and Z. Vrontisi, 2016: A global stocktake of the Paris pledges: Implications for energy systems and economy. *Glob. Environ. Chang.*, **41**, 46–63, doi:10.1016/j.gloenvcha.2016.08.006. http://www.sciencedirect.com/science/article/pii/S095937801630142X (Accessed April 6, 2017).

Vaughan, D. G., and Coauthors, 2013: Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 317–382 http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter04_FINAL.pdf.

Velders, G. J. M., D. W. Fahey, J. S. Daniel, S. O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmos. Environ.*, **123**, 200–209, doi:10.1016/j.atmosenv.2015.10.071. http://dx.doi.org/10.1016/j.atmosenv.2015.10.071.

Victor, D. G., and Coauthors, Introductory Chapter. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

von Stechow, C., and Coauthors, 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annu. Rev. Environ. Resour.*, **40**, 363–394, doi:10.1146/annurev-environ-021113-095626.

Vuuren, D. P. van, H. van Soest, K. Riahi, L. Clarke, V. Krey, E. Kriegler, M. Schaeffer, and M. Tavoni, 2016: Carbon budgets and energy transition pathways. *Environ. Res. Lett.*, **11**, 75002, doi:10.1088/1748-9326/11/7/075002.

Waldhoff, S. T., and A. A. Fawcett, 2011: Can developed economies combat dangerous anthropogenic climate change without near-term reductions from developing economies? *Clim. Change*, **107**, 635, doi:10.1007/s10584-011-0132-7.

WBGU (German Advisory Council on Global Change), 2016: *Development and justice through transformation: The Four Big "I"s*.

Weitzman, M. L., 1998: Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate. *J. Environ. Econ. Manage.*, **36**, 201–208, doi:10.1006/jeem.1998.1052.

West, J. J., and Coauthors, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nat. Clim. Chang.*, **3**, 885–889, doi:10.1038/nclimate2009. http://www.nature.com/doifinder/10.1038/nclimate2009 (Accessed April 5, 2017).

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Rev. Environ. Econ. Policy*, **11**, 115–137, doi:10.1093/reep/rew018. https://academic.oup.com/reep/article/3066306/Some.

Wigley, T. M. L., R. Richels, and J. Edmonds, 2007: *Overshoot Pathways to CO2 stabilization in a multi-gas context*. M.E. Schlesinger, H.S. Kheshgi, J. Smith, F.C. De La Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad, Eds. Cambridge University Press, Cambridge, 84-92 pp.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change*, 381–395, doi:10.1007/s10584-012-0618-y. http://link.springer.com/article/10.1007/s10584-012-0618-y (Accessed January 25, 2013).

Wollenberg, E., and Coauthors, 2016: Reducing emissions from agriculture to meet the 2 °C target. *Glob. Chang. Biol.*, **22**, 3859–3864, doi:10.1111/gcb.13340.

Xia, L., A. Robock, S. Tilmes, and R. R. Neely III, 2016: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. *Atmos. Chem. Phys.*, **16**, 1479–1489, doi:10.5194/acp-16-1479-2016.

Zeman, F. S., and D. W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philos. Trans. R. Soc. a-Mathematical Phys. Eng. Sci.*, **366**, 3901–3918, doi:10.1098/rsta.2008.0143.

Zeman, F., and K. Lackner, 2004: Capturing carbon dioxide directly from the atmosphere. *World Resour. Rev.*, **16**, 157–172. http://wordpress.ei.columbia.edu/lenfest/files/2012/11/ZEMAN_LACKNER_2004.pdf (Accessed May 11, 2015).

Zhai, C., J. H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of high climate sensitivity. *Geophys. Res. Lett.*, **42**, 8729–8737, doi:10.1002/2015GL065911. http://doi.wiley.com/10.1002/2015GL065911 (Accessed April 5, 2017).

Zickfeld, K., M. Eby, H. D. Matthews, and A. J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 16129–16134, doi:10.1073/pnas.0805800106.

Zickfeld, K., and Coauthors, 2013: Long-Term climate change commitment and reversibility: An EMIC intercomparison. *J. Clim.*, **26**, 5782–5809, doi:10.1175/JCLI-D-12-00584.1.

Zickfeld, K., and T. Herrington, 2015: The UVic Earth system climate model: model description, climatology, and applications to past, present and future climates. *Atmos.-Ocean*, **39**, L05703, doi:10.1088/1748-9326/10/3/031001. http://iopscience.iop.org/article/10.1088/1748-9326/10/3/031001/meta (Accessed April 4, 2017).

Zickfeld, K., A. H. MacDougall, and H. D. Matthews, 2016: On the proportionality between global temperature change and cumulative CO2 emissions during periods of net negative CO2 emissions. *Environ. Res. Lett.*, **11**, 55006, doi:10.1088/1748-9326/11/5/055006. http://stacks.iop.org/1748-9326/11/i=5/a=055006?key=crossref.636dc44f6dba4b8a51aeff076afe0be1.

Zomer, R. J., A. Trabucco, and D. A. Bossio, 2008: Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agric. Ecosyst. Environ.*, **126**, 67–80, doi:10.1016/j.agee.2008.01.014. http://www.sciencedirect.com/science/article/pii/S0167880908000169 (Accessed April 1, 2017).

Chapter 3: Impacts of 1.5 ºC global warming on natural and human systems

Coordinating Lead Authors: Ove Hoegh-Guldberg (Australia), Daniela Jacob (Germany), Michael Taylor (Jamaica)

Lead Authors: Marco Bindi (Italy), Ines Camilloni (Argentina), Arona Diedhiou (Cote d'Ivory/Senegal), Riyanti Djalante (Indonesia), Kristie Ebi (United States), Francois Engelbrecht (South Africa), Joel Guiot (France), Yasuaki, Hijioka (Japan), Shagun Mehrotra (United States/India), Antony Payne (United Kingdom), Sonia Seneviratne (Switzerland), Rachel Warren (United Kigdom), Guangsheng Zhou (China), Harini Nagendra (India)

Contributing Authors: R. Wartenburger (XX), K. McInnes (XX), D. Notz (XX), A. Hirsch (XX), J. Evans (XX), P. Greve (XX), W. Cheung (XX), Naota Hanasaki (Japan)

Review Editors: Jose Antonio Marengo (Brazil), Joy Periera (Malaysia), Boris Sherstyukov (Russian federation)

Chapter Scientist: Tania Guillén B. (Germany/Nicaragua)

Date of Draft: 09.04.17

Executive summary

3.1 Background and framing

This chapter presents the scientific evidence published since AR4 on observed and projected impacts and risks of global warming on natural and human systems. In addition, an assessment of avoided impacts and reduced risks at 1.5 °C compared to 2 °C warming is presented, and the implications for impacts, adaption and vulnerability of different mitigation pathways reaching 1.5 °C with and without overshooting are reviewed.

3.1.1 Scope and road map: structure of chapter

[We will develop this after we reached the final structure of the chapter. Here we also explain our approach to regional changes and hot spot regions and the box topics.]

3.1.2 Conclusions from previous assessments (SREX, AR5)

[For Internal Draft references to SREX and AR5 are made in the sub sections. We might want to state a few general findings related to a 1.5 °C warming from previous assessments. We will be prepared for the FOD after a discussion in the LAM2 on where (here or in the sub-sections) the findings should be mentioned.]

3.1.3 Refer to definitions of key terms

[Will be developed at the LAM2. Key terms will be collected from the sub-sections.]

3.1.4 Overview, storyline and relationship to other chapters

[Content will be developed at the LAM2, when we have text from all sub-sections in place. We are aiming for a coherent story line throughout the entire chapter. Here, we will also explain, how we are dealing with information coming from pathways with and without overshoot, the different time periods, and methods.]

3.1.5 End point chapter

[A paragraph about this chapter's contents - including its scope and limitations - in relation to the subsequent chapters of the report will be included.]

3.2 Methods of assessment

3.2.1 Introduction

This section presents the methods of assessment used in this chapter. These methods are varied given the breadth of the chapter, which covers both changes in climate variables, typically addressed in IPCC WG1 reports, and changes in impacts to (natural and managed) ecosystems and humans, which are typically addressed in IPCC WG2 reports. For this reason the underlying data and literature basis for our chapter is very broad. For instance, the main relevant prior IPCC material covers two chapters of the IPCC SREX report (Seneviratne et al. 2012; Handmer et al. 2012), as well as at least 5 chapters of the IPCC WG1 AR5 report (Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013; Church et al. 2013; Christensen et al. 2013) and significant parts of at least 10 chapters of the IPCC WG2 AR5 report (….). We note additionally, that several other chapters of past IPCC reports are providing useful assessments for the present report. In some cases, methods that were applied in the IPCC WG1 and WG2 reports presented differences and needed to be harmonized for the present report. In addition, the fact that changes at 1.5 °C global warming was not a focus of past IPCC reports means that dedicated approaches, in part based on the recent literature, had to be applied that are specific to the present report.

Methods applied for assessing observed and projected changes in climate and weather are presented in Section 3.2.2 and methods applied for assessing observed impacts and projected risks to natural and managed systems and human settlements are described in Section 3.2.3. Section 3.2.4 presents the methods applied to address avoided impacts in Section 3.6. Finally, in Section 3.2.5, we present the approach followed to identify "hot spots" of changes between climate at 1.5 °C vs 2 °C global warming. Background on the IPCC calibrated language, which we apply in the assessments of this chapter, is provided in Chapter 1 of this report.

3.2.2 Methods for assessing observed and projected climate and weather changes at 1.5 °C

3.2.2.1 Overview

Climate models are necessary for the investigation of the climate system response to various forcings, to perform climate predictions on seasonal to decadal time scales, and to compute projections of future climate over the coming century. On these various time frames, global climate models or downscaled output from global climate models (Section 3.2.2.3) are also being used as input to impact models to evaluate the risk related to climate change for natural and human systems.

In previous IPCC reports (e.g. IPCC 2007, IPCC 2013), climate model simulations were generally used in the context of given "climate scenarios". This means that emissions scenarios (Nakićenović and Swart 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a "storyline" framework, i.e. presenting the development of climate in the course of the 21st century and beyond if a given emissions' (and development) pathway was followed. Results were assessed for different time slices within the model projections, e.g. for 2016-2035 ("near term" (Kirtman et al. 2013), 2046-65 (mid 21st century, Collins et al. 2013), and 2081-2100 (end of 21st century, Collins et al. 2013). With a focus on climate at a given mean global temperature response (1.5 °C or 2 °C), methods of analysis needed to be developed and/or adapted for this report in order to use existing climate model simulations for this specific purpose.

In the following subsections we address the following topics. In Section 3.2.2.2, we first address the question of how to derive "climate scenarios" for given global warming limits (e.g. 1.5 °C or 2 °C warming). In

Section 3.2.2.3, we then present the climate models and associated simulations available to assess these changes in climate at given global temperature limits. In Section 3.2.2.4, we then introduce methods that have been used in previous IPCC reports for the attribution of observed changes in climate and how these can be expanded to assess changes in weather and climate associated with a global warming of 1.5 °C or 2 °C when no climate simulations are available for such assessments.

3.2.2.2 Definition of a "1.5 °C or 2 °C climate projection"

The main challenges of assessing climate changes for a 1.5 °C (or 2 °C and higher-level) global warming include the following aspects:

A. Distinguishing a) *transient climate responses* (i.e. "passing through" 1.5 °C or 2 °C global warming), b) *short-term stabilization responses* (i.e. late 21st-century output of simulations driven with emissions scenarios stabilizing mean global warming to 1.5 °C or 2 °C by 2100), and c) *long-term equilibrium stabilization responses* (i.e. output of simulations at 1.5 °C or 2 °C once climate equilibrium is reached, i.e. after several millenia). These various responses can be very different for climate variables that respond with some inertia to a given climate forcing. A striking example is sea level rise, which is projected to increase by … m within the 21st century independent of the considered scenario, but which would stabilize at very different levels for a long-term warming of 1.5 °C vs 2 °C (see Section 3.3.12).

B. The "1.5 °C or 2 °C emissions scenarios" presented in Chapter 2 are targeted at a *probable* stabilization at around 1.5 °C or 2 °C global warming. However, when these emissions scenarios are used to drive climate models, the resulting simulations include some that stabilize above these respective thresholds (typically with a probability of …., see Chapter 2). This is due both to model discrepancies and internal climate variability. For this reason, the climate outcome for any of these scenarios, even those excluding overshooting (see next point), include some probability of reaching a global climate warming higher than 1.5 °C or 2 °C. For this reason, a comprehensive assessment of "1.5 °C or 2 °C climate projections" needs to include the consideration of projections stabilizing at higher levels of warming (e.g. up to 2.5-3 °C (?), see chapter 2).

C. Some of the "1.5 °C or 2 °C emissions scenarios" of Chapter 2 include temperature overshooting over the course of the 21st century. This means that they allow for higher temperatures being reached in the course of the century (typically up to 3-4 °C) before stabilization at 1.5 °C or 2 °C is achieved by 2100. In the years of overshooting, impacts would thus correspond to higher transient temperature levels than 1.5 °C or 2 °C. For this reason, impacts for transient responses at these higher levels are also briefly addressed in Section 3.3. We note that this topic cannot be addressed in its full complexity given the short timeline of the present report and the number of aspects that would need to be addressed. Most importantly, different overshooting scenarios may have very distinct impacts depending on a) the peak temperature at overshooting, b) the length of overshooting, c) the associated rate of changes of global temperature over the time period of overshooting. While we briefly address some of these issues in Sections 3.3 and 3.6 whenever literature was available to assess these questions, we note that this question will need to be addressed more comprehensively as part of the IPCC AR6 report.

D. It was not defined prior to this report what a "1.5 °C or 2 °C" climate exactly meant. This requires an agreement on a reference time period (for 0 °C warming) and the time frame over which the global warming is assessed (e.g. 1 year, 20 years, or longer time period). As highlighted in Chapter 1, the decision for this report was to define a 1.5 °C climate as the climate in a 20-year period which displays a 1.5 °C global mean warming compared to the time period 1861-1880. We have used this definition in all assessments of this chapter. We note that this implies that mean temperature of a "1.5 °C climate" can be regionally and temporally much higher (e.g. regional annual temperature extremes displaying a warming of more than 6 °C, see Section 3.3).

Because of the short timeline of the SR15 report, there is at present a lack of climate model simulations for the low-emissions scenarios described in Chapter 2. Therefore, with a few exceptions, the present assessment needs to focus on analyses of transient responses at 1.5 °C and 2 °C (see point A. above), while short-term stabilization and long-term equilibrium stabilization responses could not be assessed in most cases due to lack of data availability (see also below). This shortfall would need to be addressed as part of the IPCC AR6 in order to provide a comprehensive assessment of changes in climate at 1.5° global climate warming. Note also that in the scenarios considered, unconventional pathways to climate mitigation are not assessed (e.g. solar radiation management). However, we provide an assessment on this topic as part of the cross-chapter box *[location TBC]*.

For the assessment of transient responses in climate at 1.5 °C vs 2 °C and higher levels of warming (Section 3.3), this assessment generally uses the same approach as Seneviratne et al. (2016), which consists of sampling the response at 1.5 °C global temperature warming from all available global climate model scenarios for the 21st century. This approach is also referred to as "time sampling" approach (James et al. 2017). Alternatively, pattern scaling, i.e. a statistical approach deriving relationships of specific climate responses as a function of global temperature change can also be used. Some assessments of this chapter are also based on this method. Its disadvantage, however, is that the relationship may not perfectly emulate the models' response in each location and for each global temperature levels (James et al. 2017). As a third approach, expert judgement can be used to assess probable changes at 1.5 °C or 2 °C by combining changes that have been attributed for the observed time period (corresponding already to a warming of 1 °C) and known projected changes at 3 °C or 4 °C (see Section 3.2.2.4).

In a few cases, assessments for short-term stabilization responses could also be assessed using a subset of model simulations that reach a given temperature limit by 2100, but overall model simulations were lacking for such assessments. Note nonetheless that for some variables (temperature and precipitation extremes) evidence suggests that responses after short-term stabilization (i.e. approximately equivalent to the RCP2.6 scenario) are very similar to the transient response of higher-emission scenarios (Seneviratne et al. 2016). This is, however, less the case for mean precipitation (e.g. Pendergrass et al. 2015) for which other aspects of the emissions scenarios appear relevant.

For the assessment of long-term equilibrium stabilization responses, this assessment uses – when available – results from existing simulations (e.g. for sea level rise). Some other results are expected from upcoming projects (e.g. the "Half a degree additional warming, prognosis and projected impacts Multimodel Intercomparison Project" (HappiMIP) (Mitchell et al. 2017), but not available at present.

3.2.2.3 Climate models and associated simulations and datasets available for the present assessment

Climate models allow for policy-relevant calculations such as the assessment of the levels of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions compatible with a specified climate stabilization target, such as the 1.5 °C or 2 °C global warming scenarios. Climate models are numerical models that can be of varying complexity and resolution (e.g. Le Treut et al. 2007). Presently, global climate models are typically Earth System Models (ESM), i.e. they entail a comprehensive representation of Earth system processes, including biogeochemical processes.

In many cases, in order to assess the impact and risk of projected climate changes on ecosystems or human systems, typical ESM simulations have a too coarse resolution (100km or more). Different approaches can be used to derive higher-resolution information. In some cases, ESMs can be run globally with very-high resolution, however, such simulations are cost-intensive and thus very rare. Another approach is to use Regional Climate Models (RCM) to dynamically downscale the ESM simulations. RCMs are limited-area models with representations of climate processes comparable to those in the atmospheric and land surface components of the global models but with a higher resolution than 100km, generally down to 10-50km (e.g. CORDEX, Jacob et al. 2014a; Cloke et al. 2013; Erfanian et al. 2016; Barlow et al. 2016) and in some cases even higher (convection permitting models, i.e. less than 4km, e.g. Kendon et al. 2014; Ban et al. 2014; Prein et al. 2015). Statistical Downscaling (SD) is another approach for downscaling information from global climate models to higher resolution. The underlying principle of SD is to develop statistical relationships that link large-scale atmospheric variables with local / regional climate variables, and to apply them to coarser-resolution models (Salameh et al. 2009; Su et al. 2016). More details on SD approaches are provided in Section 3.2.3.2.

There are various sources of climate model and downscaling information available for the present assessment. First, there are global simulations that have been used in previous IPCC assessments and which were computed as part of the World Climate Research Programme (WCRP) Coupled Models Intercomparison Project (CMIP). The IPCC AR4 report was mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. In addition, there are results from coordinated regional climate model experiments (CORDEX), which are available for different regions.

[Other topics that will discussed in the FOD]

Pre-CMIP6 simulations: Global simulations already run before the SR15 publication deadline which consider some aspects of CMIP6 (e.g. driven with Chapter 2 scenarios, etc.)

- Other models available to assess changes in regional and global climate system: e.g. models for sea level rise, hydrological models for floods, droughts, and freshwater input to oceans, cryosphere/snow models, models for sea ice, models for glaciers and ice sheets [no details but references to relevant prior IPCC chapters]

3.2.2.4 Methods for the attribution of observed changes in climate and their relevance for assessing projected changes at 1.5 °C or 2 °C global warming

As highlighted in previous IPCC reports, detection and attribution is an approach commonly applied to assess impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al. 2007; Seneviratne et al. 2012; Bindoff et al. 2013). We refer the reader to these past IPCC reports, as well as to the IPCC good practice guidance paper on detection and attribution (Hegerl et al. 2010), for more background on this topic. We note that in the IPCC framework, “attribution” means strictly “attribution to anthropogenic greenhouse gas forcing”. In some literature reports, in particular related to impacts, the term “attribution” is sometimes used in the sense of an observed impact that can be attributed to observed (regional or global) change in climate, however, without considering whether the observed change in climate is itself attributable to anthropogenic greenhouse gas forcing. This definition is not used in this chapter. However, we note that in such cases the presence of “detected” changes can be reported.

Attribution to anthropogenic greenhouse gas forcing is an important field of research for our assessments. Indeed, global climate warming has already reached 1°C compared to pre-industrial conditions (Section 3.3,), and thus “climate at 1.5 °C global warming” corresponds to approximately the addition of half a degree warming compared to present-day warming. This means that methods applied in the attribution of climate changes to human influences can be relevant for assessments of changes in climate at 1.5 °C warming, especially in cases where no climate model simulations or analyses are available for the conducted assessments. Indeed, impacts at 1.5 °C global warming can be assessed in part from regional and global climate changes that have already been detected and attributed to human influence. This is because changes that could already be ascribed to anthropogenic greenhouse gas forcing pinpoint to components of the climate system which are most responsive to this forcing, and thus will continue to be under 1.5 °C or 2 °C global warming. For this reason, when specific projections are missing for 1.5 °C global warming, some of the assessments provided in Section 3.3, in particular in Table 3.1, build upon joint assessments of a) changes that were observed and attributed to human influence up to present, i.e. for 1 °C global warming and b) projections for higher levels of warming (e.g. 2 °C, 3 °C or 4 °C) to assess the most likely changes at 1.5 °C. We note that such assessments are for transient changes only (see Section 3.2.2.2).

3.2.3 Methods for assessing observed impacts and projected risks to natural and managed systems and human settlements at 1.5 °C

3.2.3.1 Overview

Impacts are observed from datasets that are used to understand the underlying processes thanks to the development of reliable models. These models must be designed, parameters must be estimated and boundary condition set up by using data of high quality. Independent data must be used also to check the quality of the model to reproduce some present states or very different states chosen in a more or less far past (paleodata). These models are necessary to understand the complex functioning of the systems and to project future changes and then assess the risks related to changes.

The point of departure for the assessment of the analysis of impacts are local observations of physical and biological systems in all the parts of the world. The approach is inductive. Local data are collected and correlations between variables characterizing the system of study and climatic variables (mainly temperature and precipitation) are established. So syntheses by types of systems and by regions enable generalization in some way. For example, field and satellite measurements indicate substantial changes in freshwater and terrestrial ecosystems in many areas. Vegetation productivity has systematically increased over the past few decades. These changes correspond to expectations, based on experiments, models, and paleoecological responses to past warming. The particular strength of warming over the last 50 years further facilitates attribution of a major role of climate change. But a robust attribution of these changes to warming needs a better assessment of causal relationships, which is most often done using models. Signals emerging at the regional or global scale are also acknowledged as robust and may be related to global forcings.

The global distribution of observed impacts shown in AR5 (WGII chap 18) demonstrates that analyses can now detect impacts in systems strongly influenced by confounding factors and hence where climate change plays only a minor role. Enhanced research efforts would probably add additional observations of impacts with a minor, but important, role of climate to the global map.

Cascading effects must also be taken into account. Changes in atmospheric and ocean properties of the climate have driven changes in the cryosphere, on the land surface, the land subsurface, and the ocean surface. These changes have in turn led to changes in multiple aspects of hydrology and ecosystems, and in some regions changes in these systems have impacted human livelihoods. In all these cases, confidence in the role of climate change decreases for effects further down each impact chain.

3.2.3.2 Definition of a "1.5 °C or 2 °C impact projection"

As for the assessment of changes in climate at 1.5 °C vs other warming levels (Section 3.2.2.2), the comparison of impacts of 1.5 °C and 2 °C global warming needs specific methodologies. Schleussner et al. (2016) have calculated the differential effect of 1.5 °C and 2 °C global warming for the assessment of water availability and agricultural impacts. The assessment is based on an ensemble of simulations derived under the RCP8.5 scenario, using time slices centred around these specific levels of warming ("time sampling" approach that is mostly used in this chapter for transient projections of changes in climate at 1.5 °C, see Section 3.2.2.2). Schleussner et al. (2016) used the statistical comparison of the effects of both levels to conclude on their significance.

Another approach to assess impacts at 1.5 °C and 2 °C consists of driving an impact model (e.g. ecosystem model or other, see Section 3.2.3.3) with ensemble climate model simulations at different levels of warming (e.g. Guiot & Cramer 2016). However, only few such simulations are available at the time of writing.

Alternatively, projections of regional changes in climate means or extremes at 1.5° vs 2° (eg. Section 3.3) can be combined with assessments of sensitivity of impacts to these changes derived from observations or models. This combination of information requires expert judgement and underlies several assessments of impacts provided in this chapter.

3.2.3.3 Modelling approaches

Impact models are particularly important to simulate the functioning of the natural and human systems in response to climate changes. These include hydrological models and catchment basin models for water resources, vegetation dynamic models, soil models, ocean geobiochemical models, epidemiological models for health impacts, land use and land cover models, etc. Impact models often use output of regional or global climate models (see section 3.2.2.3) as input, which thus allows the computation of projected impacts (e.g. Schewe et al. 2014; Rosenzweig et al. 2014; Guiot and Cramer 2016).

Dynamical and statistical downscaling of climate models (see also Section 3.2.2.3) is particularly important for assessing impacts, given that these generally happen at a smaller scale than that simulated by global climate models. We note that while they produce climatic information at scales finer than the initial projections, both dynamical and statistical downscaling involve additional information, data, and assumptions, leading to further uncertainties and limitations of the results. This is particular true for SD because the relationships are calibrated on present-day climate and thus do not account for possible changes in climate regimes, which could affect the links between the coarser-scale and local-scale climates. In addition to issues related to resolution and model complexity, errors and uncertainties arise from observational uncertainty in evaluation data and parameterizations, choice of model domain and application of boundary conditions (driving data). In the case of SD, sources of model errors and uncertainties depend on the choice of method, including the choice of the predictors, the estimation of empirical relationships between predictors and predictands from limited data sets, and also the data used to estimate the predictors (Frost et al. 2011).

In many cases, the impacts of climate change will be experienced more profoundly in terms of the frequency, intensity or duration of extreme events (e.g., heat waves, droughts, extreme rainfall events). Extreme events are realizations of the tail of the probability distribution of weather and climate variability. They are higher-order statistics and thus generally more difficult to realistically represent in climate models. Shorter time scale extreme events are often associated with smaller scale spatial structure, which may be better represented as model resolution increases (Seneviratne et al. 2012). There is an increasing number of studies of downscaling of extremes (e.g., Katz et al. 2002; Monier and Gao 2015; Vrac and Naveau 2007; Wang et al. 2008; Emanuel et al. 2008).

3.2.3.4 Detection & attribution methods

Separation of drivers (anthropogenic climate change versus natural factors or other anthropogenic factors) from a responding system is a crucial element of formal detection and attribution analysis. The wealth of observations in ecological systems permits the application of quantitative tools for synthesis assessment of detection and attribution (Root et al. 2005). These tools include associative pattern analyses (e.g., Rosenzweig et al. 2008) and regression analyses (Chen et al. 2011), which compare expected changes due to anthropogenic climate change across multiple studies against observed changes (WGII, box 18-1).

3.2.3.5 Synthesizing aggregated impacts

To synthesize its findings in support of a risk analysis the IPCC developed the “Reasons for Concern” (RFC) concept (Smith et al. 2001), which was extensively adopted in IPCC AR4 and elaborated in (Smith et al. 2009). The goal is to establish, qualitatively, the evidence of impacts already observed that are relevant to these categories (see Glossary). The first RFC (risks to unique and threatened systems) is concerned with the potential for increased damage to systems. The second RFC is related to extreme events, which have substantial consequences on ecosystems and societies. The third RFC focuses on the disparities of impacts between regions, countries, and populations. The fourth RFC is associated with aggregate impacts, i.e. economic impacts, damages, and risks that are specifically driven by climate change at a globally aggregated level. The fifth RCP is associated with large-scale singular events or tipping points, which may be accompanied by very large impacts. The AR5 has presented the risk associated to these RFC with burning embers diagrams for which the colours vary from white (undetectable risk), yellow (moderate risk), red (high risk), to purple (very high risk), according to the global warming level.

Another method used to present the risk associated to environmental changes is the planetary boundary approach which aims to define a safe operating space for human societies to develop and thrive, based on our evolving understanding of the functioning and resilience of the Earth system (Steffen et al. 2015). The results are presented on a circular diagram with a colour gradient related to the risk probability. The operating space may be defined on the basis of the various impacts and risks analysed in this chapter: water resource (quality, quantity), ecosystem services, food security, human health, human security, etc.

3.2.4 Assessing avoided impacts at 1.5 °C vs. 2 °C and higher levels of warming

3.3 Global and regional climate changes and associated hazards: Observed changes (including paleo); attributed changes; projected risks; avoided risks at 1.5 °C

3.3.1 Global changes in climate

3.3.1.1 Introduction

The present assessment builds upon assessments from the IPCC SREX report chapter 3 (Seneviratne et al. 2012) and the IPCC AR5 WG1 report (Stocker et al. 2013; Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013; Christensen et al. 2013), as well as on more recent literature related to projections of climate at 1.5 °C and 2 °C (e.g. (Schleussner et al. 2016b; Seneviratne et al. 2016; Wartenburger et al.). More details on the applied methods of assessment are provided in Section 3.2. The main analyses of projections are based on transient evaluations of climate at 1.5 °C vs 2 °C global warming based on global climate model simulations driven with the RCP8.5 scenario (see Section 3.2.2). As discussed in Section 3.2.2, for temperature and precipitation extremes, these evaluations are approximately consistent for scenarios stabilizing close to 1.5 °C or 2 °C global warming (RCP 2.6), however they may differ for other quantities (e.g. mean precipitation). Table 3.1 provides a summary of the main global changes in climate associated with a 1.5 °C global warming as assessed in the following subsections.

3.3.1.2 Global changes in temperature and precipitation

3.3.1.2.1 Observed and attributed changes

Warming of the Global Mean Surface Temperature (GMST) compared to pre-industrial levels has at the time of writing this report (2017) reached approximately 1 °C (Chapters 1 and 2). At the time of writing the AR5 WG1 report (i.e. for time frames up to 2012, Stocker et al. 2013), Hartmann et al. (2013) assessed that the globally averaged combined land and ocean surface temperature data as calculated by a linear trend, showed a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012, when multiple independently produced datasets existed, and about 0.72 [0.49 to 0.89] °C over the period 1951–2012. Hence most of the global warming has occurred since 1950 and it has continued substantially in recent years. These values are for global mean warming, however, regional trends can be much more varied (Figure 3.1). With few exceptions, most land regions display stronger trends in the global mean average, and by 2012, i.e. with a warming of ca. 0.85 °C (see above), some land regions already displayed warming higher than 1.5 °C (Figure 3.1). Hence, as highlighted in further subsections, it is important to take into account that a 1.5 °C or 2 °C warming implies much larger regional warming on land.

[INSERT FIGURE 3.1 HERE]

Figure 3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. From Stocker et al. (2013)

A large fraction of the detected global warming has been attributed to anthropogenic forcing (Bindoff et al. 2013). The AR5 (Bindoff et al. 2013) assessed that it is *virtually certain* that human influence has warmed the global climate system and that it is *extremely likely* that human activities caused more than half of the observed increase in GMST from 1951 to 2010 (see supplementary Figure S3.1). The AR5 (Bindoff et al. 2013) assessed that greenhouse gases contributed a global mean surface warming *likely* to be between 0.5 °C and 1.3 °C over the period 1951–2010, with the contributions from other anthropogenic forcings *likely* to be between – 0.6 °C and 0.1 °C, from natural forcings *likely* to be between – 0.1 °C and 0.1 °C, and from internal variability *likely* to be between –0.1 °C and 0.1 °C.

An area in which substantial new literature is available since the AR5 is the global mean surface temperature trend during the so-called "global warming hiatus" (Stocker et al. 2013; Karl et al. 2015; Lewandowsky et al. 2016). This term was used to refer to an apparent slowdown of GMST warming since 1998. Recent publications have highlighted that this "slow-down" was possibly overestimated at the time of the AR5 due to issues with data corrections, in particular related to coverage (Cowtan and Way 2014; Karl et al. 2015; see Figure S3.2). In addition, there is evidence that this response was due in part to lower surface heating of the oceans but higher heating at depth, and thus that it did not reflect any slowdown in the overall heating of the Earth's climate system (Yang et al. 2016). There is substantial evidence supporting this latter assessment, including the continued meltdown of the Arctic sea ice (Stocker et al. 2013), unabated increase in global sea level (Stocker et al. 2013), and a continued strong warming of hot extremes over land (Seneviratne et al. 2014) during that time period. For this reason, as pointed by some authors (e.g. Seneviratne et al. 2014; Yang et al. 2016), one should note that the GMST warming is not necessarily the most accurate measure to assess the level of greenhouse gas forcing on the Earth's climate system in a transient climate context.

Observed global changes in the water cycle are more uncertain than observed changes in temperature (Hartmann et al. 2013; Stocker et al. 2013). The AR5 assessed that it is very likely that global near surface and tropospheric air specific humidity have increased since the 1970s (Hartmann et al. 2013). However, it also highlighted that during recent years the near surface moistening over land has abated (*medium confidence*), and that as a result, there have been fairly widespread decreases in relative humidity near the surface over the land in recent years (Hartmann et al. 2013). With respect to precipitation, some regional precipitation trends appear to be robust (Stocker et al. 2013), but when virtually all the land area is filled in using a reconstruction method, the resulting time series of global mean land precipitation shows little change since 1900. Hartmann et al. (2013) highlight that confidence in precipitation change averaged over global land areas since 1901 is low for years prior to 1951 and medium afterwards. However, for averages over the mid-latitude land areas of the Northern Hemisphere, Hartmann et al. (2013) assessed that precipitation has likely increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudinal zones area-averaged long-term positive or negative trends have low confidence due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al. 2013). For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013).

3.3.1.2.2 Projected changes at 1.5 °C

Figure 3.2 includes maps of projected changes in local mean temperature warming at 1.5 °C vs 2 °C global mean warming. Similar analyses are provided for temperature extremes (changes in the maximum temperature of the local hottest day of the year, TXx, and in the minimum temperature of the local coldest day of the year, TNn) in Figure 3.2. The responses for both analyses are derived from transient simulations of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) for the RCP8.5 scenario, similarly as in Seneviratne et al. (2016). As highlighted in Section 3.2.1, the results are similar for other emissions scenarios, and for 1.5 °C in particular with responses of simulations for the RCP2.6 scenario, which stabilize below / at around 2 °C (see Supplementary Figure S3.3).

[INSERT FIGURE 3.2 HERE]

Figure 3.2: Projected local mean temperature warming at 1.5 °C global warming (left), 2.0 °C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016)). Note that the warming at 1.5 °C GMST warming is similar for RCP2.6 simulations (see Supplementary Figure S3.3).

Figures 3.2 and 3.3 highlight some important features. First, because of the land-sea warming contrast (e.g. Collins et al. 2013; Christensen et al. 2013; Seneviratne et al. 2016), the warming on land is much stronger than on the oceans, which implies that at 1.5 °C warming several land regions display a higher level of mean warming (Figure 3.1). In addition, as highlighted in Seneviratne et al. (2016), this feature is even stronger for temperature extremes (Figure 3.2; see also Section 3.3.2 for a more detailed discussion). Second, even for a small change in global warming (0.5 °C) between the two considered global temperature limits (1.5 °C and 2 °C) substantial differences in mean temperature, and in particular in extreme temperature warming can be identified on land, as well as over sea in the Arctic. In some locations these differences are larger than 2-2.5 °C (Figure 3.2) and thus 4-5 times larger than the differences in global mean temperature. These regional differences are addressed in more detail in Section 3.3.2.

[INSERT FIGURE 3.3 HERE]

Figure 3.3: Projected local warming of extreme temperatures (top: Annual maximum daytime temperature, TXx; bottom: Annual minimum nighttime temperature, TNn) warming at 1.5 °C global warming (left), 2.0 °C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016). Note that the warming at 1.5 °C GMST warming is similar for RCP2.6 simulations (see Supplementary Figure S3.4).

Figure 3.4 displays the projected changes in mean precipitation and heavy precipitation (5-day maximum precipitation, Rx5day) at 1.5 °C, 2 °C and their difference, using the same approach as for Figures 3.1 and 3.2 (see also Methods, Section 3.2.2). The differences for precipitation are less clear than for temperature mean and extremes. However, some regions display substantial changes in mean precipitation between 1.5 °C vs. 2 °C global warming, in particular decreases in the Mediterranean area, including Southern Europe, the Arabian Peninsula and Egypt. There are also changes towards increased heavy precipitation in some regions, as highlighted in Section 3.3.3, although the differences are generally small between 1.5 °C and 2 °C global warming (Figure 3.4).

[INSERT FIGURE 3.4 HERE]

Figure 3.4: Projected changes of mean (top) and extreme (5-day maximum precipitation) precipitation at 1.5 °C global warming (left), 2.0 °C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016). Note that the response at 1.5 °C GMST warming is similar for the RCP2.6 simulations (see Supplementary Figure S3.5).

Analyses have also been performed to assess changes in the risks of exceeding pre-industrial thresholds for temperature and precipitation extremes. Results suggest substantial differences in risks for very hot extremes already between 1.5 °C and 2 °C, both on global and regional scale (Fischer and Knutti 2015; see also Figure 3.5, left). The differences are more moderate for heavy precipitation (Figure 3.5, right), also consistent with the analyses in Figure 3.4.

[INSERT FIGURE 3.5 HERE]

Figure 3.5: Probability ratio of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature (left) and precipitation (right) at a given warming level relative to pre-industrial conditions averaged across land [from Fischer and Knutti (2015)].

3.3.1.3 Summary on global changes in key climate variables and climate extremes

Table 3.1 below provides a summary of detected, attributed, and projected changes at 1.5° and 2° global warming for several climate variables, including climate extremes. The underlying data basis is the IPCC SREX report Chapter 3 (Seneviratne et al. 2012), several chapters of the AR5 WG1 report (Hartmann et al. 2013; Bindoff et al. 2013; Collins et al. 2013), and new evidence in publications since AR5 (including analyses displayed in this Chapter). The projections are assessed both based on transient simulations (i.e. passing through 1.5 °C or 2 °C, including overshoot) and based on projected changes at equilibrium (based on HappiMIP experiment *[Not yet available]*, Mitchell et al. (2017). More details on the applied methods are provided in Section 3.2.

[INSERT TABLE 3.1 HERE]

Table 3.1: Summary on global changes in key climate variables and climate extremes: Detected observed changes, attributed observed changes, and projected changes at 1.5 °C and 2 °C global warming, including both transient changes and changes at equilibrium. Assessments are provided qualitatively (top half of cell) and if available also quantitatively (bottom half of cell). Symbols for references are: S12 (Seneviratne et al. 2012), H13 (Hartmann et al. 2013), B13 (Bindoff et al. 2013), and C13 (Collins et al. 2013).

	Detected observed changes	**Attributed observed changes**	**Projected transient changes until 2100 (passing through)**		**Projected changes at equilibrium**	
			1.5°C	**2°C (transient or over-shoot)**	**1.5°**	**2°**
Mean temperature	**Globally**: ***Virtually certain*** increase [B13]; **Regionally**: ***Very likely*** increase in most regions [REFS?] **Globally**: ~1° global surface warming [REFS?]; **Regionally**: Higher detected warming than 1°C in many regions [REFS?]	**Globally**: ***Virtually certain*** human influence on increase [B13] **Regionally**: ***Very likely*** human influence on increase in most regions [REFS?] **Globally**: ***Likely*** 0.5-1.3°C warming over 1951-2010 time period [B13] **Regionally**: ?[REFS?]	**Globally**: ***Virtually certain*** increase [assessment based on observed and attributed changes] **Regionally**: ***Very likely*** increase in most regions [assessment based on observed and attributed changes] **Globally**: 1.5°C **Regionally: *Very likely*** higher warming than 1.5°C in most land regions (on average between 1.5°C-3°C depending on region) [Fig. 3.3.1]	**Globally**: ***Virtually certain*** increase [assessment based on observed and attributed changes] **Regionally**: ***Very likely*** increase in most regions [assessment based on observed and attributed changes, and C13 for CMIP5 projections] **Globally**: 2°C **Regionally: *Very likely*** higher warming than 2° on land (on average between to 2-4° depending on region) [Fig. 3.3.1]	Not yet availa -ble (Happ i-MIP exper i- ment s)	Not yet availa -ble (Happ i-MIP exper i- ment s)
Mean precipitation	**Globally*: Low confidence*** in global trends in mean precipitation [H13] ***Low confidence*** in trends in monsoons because of insuffi-cient evidence. [S12]	**Globally:** No attribution on global scale [REF?] ***Low confidence*** in human influence on trends in monsoons due to insufficient evidence. [S12]	TO BE ASSESSED, probably ***Low confidence***	TO BE ASSESSED, probably ***Low confidence***	Not yet availa ble	Not yet availa ble

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Temperature extremes (hot and cold extremes)	**Globally: *Very likely*** increase in number of warm days/nights and decrease in number of cold days/nights (S12, H13) **Regionally**: See section 3.3.2	**Globally**: ***Very likely*** anthropogenic influence on trends in warm/cold days/nights at the global scale. [B13] **Regionally**: No attribution of trends at a regional scale with a few exceptions. [S12, B13]	**Globally: *Very likely*** further increase in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes [assessment based on observed and attributed changes, and based on Fig. 3.3.2] **Regionally**: ***Likely*** increase in most land regions [Fig. 3.3.2; Section 3.3.2] **Globally**: - **Regionally: *Likely*** higher warming than 1.5°C in most land regions (on average between 2°C-6°C depending on region and considered extreme index) [Fig. 3.3.2; Section 3.3.2]	**Globally: *Virtually certain*** further increase in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes [assessment based on S12 and C13 for CMIP5 projections] **Regionally**: ***Very likely*** increase in most land regions [Fig. 3.3.2; Section 3.3.2] **Globally**: - **Regionally: *Likely*** higher warming than 2°C in most land regions (on average between 3°-8° depending on region and considered extreme index) [Fig. 3.3.2; Section 3.3.2]	Not yet availa ble	Not yet availa ble
Heavy precipitation	**Globally**: ***Likely*** more regions with increase than regions with decreases (S12)	**Globally**: ***Medium confidence*** that human influences have contributed to intensification of extreme precipitation at the global scale (S12)	**Globally: *Medium confidence*** in further increase in more regions than in regions with decrease [Fig. 3.3.3]	**Globally: *Medium confidence*** in further increase in more regions than in regions with decrease [Fig. 3.3.3]	Not yet availa ble	Not yet availa ble

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Droughts and dryness	**Globally:** *Medium confidence* that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but opposite trends also exist [S12]. No support for increasing drying in dry regions and increasing wetting in wet regions, except in high latitudes (Greve et al. 2014)	**Globally:** *Medium confidence* that anthropogenic influence has contributed to some observed changes in drought patterns. *Low confidence* in attribution of changes in drought at the level of single regions due to inconsistent or insufficient evidence. [S12]	**Globally:** *Medium confidence* that some trends patterns could be enhanced, in particular in the Mediterranean region [assessment based on observed trends, Fig. 3.3.3, Fig. 3.3.4.X, and Section 3.3.4]	**Globally:** *Medium confidence* that some trends patterns could be enhanced, in particular in the Mediterranean region [assessment based on observed trends, Fig. 3.3.3, Fig. 3.3.4.X, and Section 3.3.4]	Not yet availa ble	Not yet availa ble
Storms and tropical cyclones	**Globally:** *Likely* poleward shift in *extratropical cyclones*. [S12] *Low confidence* that any observed long-term (i.e., 40 years or more) increases in *tropical cyclone* activity are robust, after accounting for past changes in observing capabilities. **Regionally:** *Low confidence* in regional changes in intensity of *extratropical cyclones*. [S12]	**Globally:** *Medium confidence* in an anthropogenic influence on poleward shift. [S12] *Low confidence* in attribution of any detectable changes in tropical cyclone activity to human influences (due to uncertainties in historical tropical cyclones record, incomplete understanding of physical mechanisms, and degree of tropical cyclone variability). [S12]	**Globally:** *Medium confidence* in projected poleward shift of mid-latitude storm tracks. [based on assessment for observed changes] *Low confidence* in changes in tropical cyclones [based on observed and attributed changes]	**Globally:** *Medium confidence* in projected poleward shift of mid-latitude storm tracks. [based on assessment for observed changes] *Low confidence* in changes in tropical cyclones [based on observed and attributed changes]	Not yet availa ble	Not yet availa ble

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Runoff and flooding	**Globally:** ***Low confidence*** at the global scale regarding even the sign of observed changes in frequency or magnitude of floods [S12] ***High confidence*** in trend toward earlier occurrence of spring peak river flows in snowmelt- and glacier-fed rivers. [S12]	**Globally:** ***Low confidence*** that anthropogenic warming has affected the magnitude or frequency of floods at a global scale. ***Medium confidence to high confidence*** in anthropogenic influence on changes in some components of the water cycle (precipitation, snowmelt) affecting floods.	**Globally:** ***Low confidence*** in global projections of changes in flood magnitude and frequency because of insufficient evidence. [based on observed and attributed changes, and S12 for RCP8.5 projections] ***Medium confidence*** (based on physical reasoning) that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions [based on S12]	**Globally:** ***Low confidence*** in global projections of changes in flood magnitude and frequency because of insufficient evidence. [based on observed and attributed changes, and S12 for RCP8.5 projections] ***Medium confidence*** (based on physical reasoning) that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions [based on S12]	Not yet availa ble	Not yet availa ble
Winds	**Globally:** ***Low confidence*** in trends due to insufficient evidence [S12]	**Globally:** ***Low confidence*** in the causes of trends due to insufficient evidence. [S12]	**Globally:** ***Low confidence*** in projected changes [based on observed and attributed changes and lack of assessments for 1.5°C global warming]	**Globally:** ***Low confidence*** in projected changes [based on observed and attributed changes and lack of assessments for 2°C global warming]	Not availa ble	Not availa ble
Snow and permafrost	***Likely*** increased thawing of permafrost with *likely* resultant physical impacts. [S12] -- NEED ASSESSMENT FOR SNOW	***Likely*** anthropogenic influence on thawing of permafrost [S12] -- NEED ASSESSMENT FOR SNOW	***Likely*** increased thawing of permafrost with *likely* resultant physical impacts. [based on assessment for observed changes] - NEED ASSESSMENT FOR SNOW	***Likely*** increased thawing of permafrost with *likely* resultant physical impacts. [based on assessment for observed changes] - NEED ASSESSMENT FOR SNOW	Not availa ble	Not availa ble

	Detected observed changes	Attributed observed changes	Projected transient changes until 2100 (passing through)		Projected changes at equilibrium	
			1.5°C	2°C (transient or over-shoot)	1.5°	2°
Ocean chemistry	Very high confidence in decrease in pH, oxygen and carbonate, while similar confidence increase in bicarbonate and protons	Almost certain decrease in oxygen content due to warming trends.. Charges in carbonate chemistry almost certainly driven by increasing carbon dioxide content (high confidence)	Progress changes in risk. Risk increases with increase in ocean temperature and carbon dioxide content.	High confidence in impacts being higher with higher temperature and carbon dioxide.	Not availa ble	Not availa ble
Ocean circulation	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availa ble	Not availa ble
Sea ice	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	TO BE ASSESSED	Not availa ble	Not availa ble
Sea level (mean & extremes)	**Globally**: [[ASSESSMENT FOR MEAN SEA LEVEL?]] ***Likely*** increase in extreme coastal high water worldwide related to increases in mean sea level in the late 20th century. [S12]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] ***Likely*** anthropogenic influence on extreme coastal high water worldwide via mean sea level contributions [S12]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] ***Likely*** increase in extreme coastal high water worldwide via mean sea level contributions [based on observed and attributed changes]	**Globally:** [[ASSESSMENT FOR MEAN SEA LEVEL?]] ***Likely*** increase in extreme coastal high water worldwide via mean sea level contributions [based on observed and attributed changes]	Not yet availa ble	Not yet availa ble

3.3.2 Temperature on land, including extremes

This section addresses regional changes in temperature on land, with a focus on extreme temperatures.

3.3.2.1 Observed and attributed changes

The AR5 assessed that it is *certain* that globally averaged land surface air temperature has risen since the late 19th century and that this warming has been particularly marked since the 1970s (Hartmann et al. 2013). While the quality of temperature ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al. 2012), it should be noted that some regions are undersampled. In particular, Cowtan and Way (2014) recently highlighted issues regarding undersampling being concentrated at the Poles and over Africa, which may lead to biases in estimated changes in global mean surface temperature (see also Section 3.3.1.2.1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature. The attribution chapter of the AR5 (Bindoff et al. 2013) assessed that over every continental region, except Antarctica, it is *likely* that anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century. Further, it assessed that it is *likely* that there has been an anthropogenic contribution to the very substantial Arctic warming since the 1960s. Bindoff et al. (2013) also assessed that anthropogenic influence has *likely* contributed to temperature change in many sub-continental regions.

Regarding observed changes in temperature extremes, the IPCC SREX report assessed (Seneviratne et al. 2012) that since 1950 it is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for land areas with sufficient data (see also Table 3.1). It also assessed that it is *likely* that such changes have occurred at the continental scale in North America, Europe, and Australia, that there is *medium confidence* in a warming trend in daily temperature extremes in much of Asia, and that there is *low to medium confidence* in historical trends in daily temperature extremes in Africa and South America depending on the region. Further Seneviratne et al. (2012) assessed that globally, in many (but not all) regions with sufficient data there is *medium confidence* that the length or number of warm spells or heat waves has increased since the middle of the 20th century, and that it is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale. Hence, observed and attributed changes in both mean and extreme temperature consistently point to a widespread influence of human-induced warming in most land regions.

3.3.2.2 Projected changes in temperature at 1.5 °C vs. 2 °C

We can expect that a further increase of 0.5 °C or 1 °C will be detectable because changes in mean and extreme temperatures can already be detected at global and also continental scale (see previous subsection), i.e. for a global warming of 1 °C.

We provide an assessment of differences in projections at 1.5 °C vs 2 °C global warming using the empirical scaling approach presented in Section 3.2 (building upon Seneviratne et al. 2016). Figure 3.6 displays for the IPCC SREX regions (see Section 3.2. for an overview) changes in temperature hot extremes (annual maximum daytime temperature, TXx) as a function of global mean temperature warming. The plot insets display the full range of CMIP5 simulations (orange range for RCP8.5 simulations, blue range for RCP2.6 simulations) as well as the mean response for both simulation ensembles (orange and blue lines, respectively). As highlighted in previous publications (Seneviratne et al. 2016; Wartenburger et al.), the mean climate model response of changes in the absolute temperature of extremes is found to be approximately linear and independent of the considered emission scenario. This implies that the transient response (inferred from the RCP8.5 simulations) is close the equilibrium response (corresponding to the RCP2.6 simulations).

[INSERT FIGURE 3.6 HERE]

Figure 3.6: Projected changes in annual maximum daytime temperature (TXx9 as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al.).

[INSERT FIGURE 3.7 HERE]

Figure 3.7: Projected changes in annual minimum nighttime temperature (TNn) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al.).

We see a stronger warming of the regional land-based hot extremes compared to the mean global temperature warming in most land regions (also discussed in Seneviratne et al. 2016). The regions displaying the stronger contrast are Central North America, Eastern North America, Central Europe, Southern Europe/Mediterranean, Western Asia, Central Asia, and Southern Africa. As highlighted in Vogel et al. (2017), the location of these regions can be related to their climate regimes, which are associated with strong soil moisture-temperature coupling (related to a transitional soil moisture regime Koster et al. 2004;

Seneviratne et al. 2010). Due to enhanced drying in these regions (see Section 3.3.4), evaporative cooling is decreased, leading to a regional added warming compared to the global temperature response. In general, these regions also show the largest spread in temperature extremes response, likely related to the impact of the soil moisture-temperature coupling for the overall response. This spread is due to both intermodel variations in the representation of drying trends (Orlowsky and Seneviratne 2013; Greve and Seneviratne 2015) and to differences in soil moisture-temperature coupling in climate models (Seneviratne et al. 2013a; Stegehuis et al. 2013; Sippel et al. 2016) , whereby also feedbacks with clouds and surface radiation are relevant (Cheruy et al. 2014). Furthermore, in some regions also internal climate variability can explain the spread in projections (Deser et al. 2012). Regions with the most striking spread in projections of hot extremes include Central Europe, with projected regional TXx warming at 1.5 °C ranging from 1 °C to 5 °C warming, and Central North America, which displays projected changes at 1.5 °C global warming ranging from no warming to 4 °C warming (Figure 3.6).

Figure 3.7 displays similar analyses as Figure 3.6 but for the annual minimum nighttime temperatures, TNn. The mean response of these cold extremes display less discrepancy with the global levels of warming (often close to the 1:1 line in many regions), however, there is a clear amplified warming in regions with snow and ice cover. This is expected given the Arctic warming amplification (Serreze and Barry 2011), which is to a large part due to snow-albedo-temperature feedbacks (Hall and Qu 2006). In some regions and for some model simulations, the warming of TNn at 1.5 °C global warming can reach up to 8 °C regionally (e.g. Northern Europe, Figure 3.7) and thus be much larger than the global temperature warming.

Figure 3.8 additionally displays maps of changes in the number of hot days (NHD) and number of frost days (NFD) at 1.5 °C and 2 °C global mean surface temperature warming. These analyses reveal clear patterns of changes between the two warming levels. For the number of hot days, the largest differences are found in the tropics due to the lower interannual temperature variability (Mahlstein et al. 2011), and despite the tendency for higher absolute changes in hot extremes (Figure 3.6). The changes in the number of frost days are expectedly particularly strong in the Arctic (decrease of 60 days in some regions, i.e. about 2 months). These changes are also of high relevance for changes in snow and ice cover in the affected regions (see discussion of changes in snow and permafrost, and sea ice in Sections 3.3.8 and 3.3.11, respectively).

[INSERT FIGURE 3.8 HERE]

Figure 3.8: Projected changes in number of hot days (10% warmest days) and in number of frost days (days with T<0 °C) at 1.5 °C (left) and 2 °C (right) GMST warming, and their difference (right). Adapted from (Wartenburger et al.)

3.3.3 Precipitation, including heavy precipitation and monsoons

This section addresses regional changes in precipitation on land, with a focus on heavy precipitation, and a consideration of changes in monsoon precipitation. As discussed in Section 3.1.2, observed and projected changes in precipitation are more uncertain than for temperature.

3.3.3.1 Observed and attributed changes

The AR5 (Bindoff et al. 2013) assessed that when considering just land regions with sufficient observations, the largest signal of differences in mean precipitation between models with and without anthropogenic forcings is in the high latitudes of the Northern Hemisphere, where increases in precipitation are a robust feature of climate model simulations.

For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013). The SREX assessed that it is *likely* that there have been statistically significant increases in the number of heavy precipitation events (e.g., 95th percentile) in more regions than there have been statistically significant decreases, but it also highlighted that there are strong regional and subregional variations in the trends (Seneviratne et al. 2012). Further, it highlighted that many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The IPCC SREX (Seneviratne et al. 2012) assessed that the overall most consistent trends toward heavier precipitation events are found in North America (*likely* increase over the continent). It provided further detailed regional assessments of observed trends in heavy precipitation have been provided (Seneviratne et al. 2012).

For monsoons, the SREX assessed that there is *low confidence* in trends in monsoons because of insufficient evidence (Seneviratne et al. 2012; see also Table 3.1). There are a few new available assessments (Singh et al. 2014), who showed that using precipitations observations (1951-2011) of the South Asian summer monsoon there have been significant decreases in peak-season precipitation over the core-monsoon region and significant increases in daily-scale precipitation variability. However, there is not sufficient evidence to revise the SREX assessment of *low confidence* in overall observed trends in monsoons.

3.3.3.2 Projected changes in precipitation at 1.5 °C vs. 2 °C

Section 3.3.1.2.2 summarizes the projected changes in mean precipitation displayed in Figure 3.4. Some other evaluations are also available for some regions. For instance, Déqué et al. (2016) investigates the impact of a 2 °C global warming on precipitation over tropical Africa and found that average precipitation does not show a significant response due to two compensating phenomena: (a) the number of rain days decreases whereas the precipitation intensity increases, and (b) the rain season occurs later during the year with less precipitation in early summer and more precipitation in late summer. We note that the assessment of insignificant differences between 1.5 °C and 2 °C scenarios for tropical Africa is consistent with the results of Figure 3.4.

Regarding changes in heavy precipitation, Figure 3.9 displays projected changes in the 5-day maximum precipitation (Rx5day) as function of global temperature warming, using a similar approach as in Figures 3.6 and 3.7. This analysis shows that projected changes in heavy precipitation are more uncertain than for temperature extremes. However, the mean response of the model simulations is generally robust and linear (see also Fischer et al. 2014; Seneviratne et al. 2016). As highlighted in Seneviratne et al. (2016), this response is also found to be mostly independent of the considered emissions scenario (e.g. RCP2.6 vs. RCP8.5 in Figure 3.9). This appears to be a specific feature of heavy precipitation, possibly due to a stronger coupling with temperature, as the scaling of projections of mean precipitation changes with global warming shows some scenario dependency (Pendergrass et al. 2015). An analysis by Wartenburger et. al. suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5 °C vs. 2 °C.

[More regional details to be added in FOD]

Projected changes in monsoons at 1.5 °C and 2 °C compared to present have not been assessed in the literature so far. At the time of the IPCC SREX report, the assessment was that there was *low confidence* in overall projected changes in monsoons (for high-emissions scenarios) because of insufficient agreement between climate models (Seneviratne et al. 2012). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios. Jiang and Tian (2013), who compared the results of 31 and 29 reliable climate models under the SRES A1B scenario or the RCP4.5 scenario, respectively, found little projected changes in the East Asian winter monsoon as a whole relative to the reference period (1980-1999). Regionally, they found a weakening north of about 25°N in East Asia and a strengthening south of this latitude, which result from atmospheric circulation changes over the western North Pacific and Northeast Asia owing to the weakening and northward shift of the Aleutian Low, and from decreased northwest-southeast thermal and sea level pressure differences across Northeast Asia. In summer, Jiang and Tian (2013) found a projected slight strengthening of monsoon in East China over the 21st century as a consequence of an increased land-sea thermal contrast between the East Asian continent and the adjacent western North Pacific and South China Sea. Using six CMIP5 model simulations of the RCP8.5 high-emission scenario, Jones and Carvalho (2013) showed that future changes in the South American Monsoon System (SAMS) are increased in seasonal amplitudes, early onsets, late demises and durations of the SAMS. The simulations for this scenario project a 30% increase in the amplitude from the current level by 2045-50. In addition, the RCP8.5 scenario projects an ensemble mean decrease of 14 days in the onset and 17-day increase in the demise date of the SAMS by 2045-50. The most consistent CMIP5 projections analysed confirmed the increase in the total monsoon precipitation over southern Brazil, Uruguay, and northern Argentina. Given that scenarios at 1.5 °C or 2 °C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) and Jones and Carvalho (2013), we assess that there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding differences in responses at 1.5 °C vs. 2 °C.

[INSERT FIGURE 3.9 HERE]

Figure 3.9: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger et al.).

3.3.4 Drought and dryness

3.3.4.1 Observed and attributed changes

The IPCC SREX assessed that there is *medium confidence* that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but that opposite trends also exist (Seneviratne et al. 2012). It also assessed that there is *medium confidence* that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes, though it also pointed to the fact that temperature can only be indirectly related to drought trends (e.g. Sheffield et al. 2012). However there is *low confidence* in the attribution of changes in droughts at the level of single regions due to inconsistent or insufficient evidence (Seneviratne et al. 2012). Recent analyses have not provided support for the detection of increasing drying in dry regions and increasing wetting in wet regions, except in high latitudes (Greve et al. 2014), thus revising the AR5 assessment (Hartmann et al. 2013) on this point.

3.3.4.2 Projected changes in drought and dryness at 1.5 °C vs. 2 °C

Projections of changes in drought and dryness for high-emissions scenarios (e.g. RCP8.5 corresponding to ca. 4 °C global warming) are uncertain in many regions, and also dependent on considered drought indices (e.g. Seneviratne et al. 2012; Orlowsky and Seneviratne 2013). Uncertainty is expected to be even larger for conditions of smaller signal-to-noise ratio such as for global warming levels of 1.5 °C and 2 °C. Figure 3.10 from (Greve *XXXX*), derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The analysed simulations span the full range of available emissions scenarios and the sensitivities are derived using a modified pattern scaling approach. The applied approach assumes linear dependencies on global temperature changes while thoroughly addressing associated uncertainties via resampling methods. Northern high latitude regions display robust responses towards a wetting, while subtropical regions display a tendency towards drying but with a large range of responses. Even though both internal variability and the scenario choice play an important role in the overall spread of the simulations, the uncertainty stemming from the climate model choice usually accounts for about half of the total uncertainty in most regions (Greve *XXXX*). An assessment of the implications of limiting global mean temperature warming to values below (i) 1.5 °C or (ii) 2 °C show that opting for the 1.5 °C -target might just slightly influence the mean response, but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve *XXXX*).

[INSERT FIGURE 3.10 HERE]

Figure 3.10: Conceptual summary of the likelihood of increases/decreases in P-E considering all climate models and all scenarios. Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean temperature change averaged for each SREX regions outlined in the map (from Greve *XXXX*).

3.3.5 Wind

Wind change assessments are usually motivated by a need to understand changes in the sector for which they are relevant such as agriculture (McVicar et al. 2008; Vautard et al. 2010); wind energy (Pryor and

Barthelmie 2010; Troccoli et al. 2012) wave climate (Hemer et al. 2013; Hemer and Trenham 2016 and Young et al. 2011 for assessing changes in ocean waves). Extreme wind hazard is most meaningfully assessed in terms of the specific meteorological storms (e.g. Walsh et al. 2016) whereby factors such as changes in the region over which the storms occur (e.g. Kossin et al. 2014), changes in frequency and intensity of the storms, and how they are influenced by modes of natural variability are relevant considerations.

Projections in winds have found increases in 10 m mean and 99th percentile winds in high latitude ocean regions particularly in winter in CMIP3 models (McInnes et al. 2011). This in turn influences wave climate projections with robust increases in waves projected in the southern ocean in CMIP3 models (Hemer et al. 2013b). While projected changes in mean winds are generally small, there is the potential for large changes in wind characteristics (including for example directions or extremes) at the boundaries of major circulation features that are projected to undergo future shifts in location. For example O'Grady et al. (2015) find changes in predominant wind direction in CMIP 5 models during summer in southeastern Australia with potential consequences for longshore sediment transport due to the projected poleward movement of the subtropical ridge in southeastern Australia. The southward expansion of the region affected by tropical cyclones (e.g. Kossin et al. 2014) may change the likelihoods of extreme winds if tropical cyclone regions of occurrence expand towards the poles.

Over the oceans, (Zheng et al. 2016) confirmed that the global oceanic sea-surface wind speeds increased at a significant overall rate of 3.35 cm s^{-1} yr^{-1} for the period 1988–2011 and that only a few regions exhibited decreasing wind speeds without significant variation over this period. The increasing wind speeds were more noticeable over the Pacific low-latitude region than over region of higher latitude. Wind speeds trends over the western Atlantic were stronger than those over the eastern Atlantic, while the south Indian Ocean winds were stronger than that those over the north Indian Ocean. This confirmed by (Ma et al. 2016) who showed that the surface wind speed has not decreased in the averaged tropical oceans. (Liu et al. 2016) used twenty years (1996–2015) of satellite observations to study the climatology and trends of oceanic winds and waves in the Arctic Ocean in the summer season (August–September). The Atlantic-side seas, exposed to the open ocean, host more energetic waves than those on the Pacific side. Waves in the Chukchi Sea, Beaufort Sea (near the northern Alaska), and Laptev Sea have been significantly increasing at a rate of 0.1–0.3 m $decade^{-1}$. The trend of waves in the Greenland and Barents Seas, on the contrary, is weak and not statistically significant. In the Barents and Kara Seas, winds and waves initially increased between 1996 and 2006 and later decreased. Large-scale atmospheric circulations such as the Arctic Oscillation and Arctic dipole anomaly have a clear impact on the variation of winds and waves in the Atlantic sector.

3.3.6 Storms and tropical cyclones

There is increasing evidence that the number of very intense tropical cyclones have increased in recent decades across most ocean basins, with associated deceases in the overall number of tropical cyclones (Elsner et al. 2008; Holland and Bruyère 2014). This result holds in particular over the North Atlantic, North Indian and South Indian Ocean basins (e.g. Singh et al. 2000; Singh 2010; Kossin et al. 2013; Holland and Bruyère 2014). It should be noted that these results are largely based on the observational record of the satellite era (the last two to three decades), since the tropical cyclone observational record is extremely heterogeneous before this period (e.g. Walsh et al. 2016b). Coupled global climate model (CGCM) projections of the changing attributes of tropical cyclones under climate change are consistently indicative of increases in the global number of very intense tropical cyclones (e.g. Christensen et al. 2013). Model projections are also indicative of general decreases of tropical cyclone frequencies under climate change, although more uncertainties are associated with such projections at the ocean basin scale (e.g. Knutson et al. 2010; Sugi and Yoshimura 2012; Christensen et al. 2013). A general theory explaining these findings, and thereby strengthening confidence in the projections, has recently been proposed. This theory states that under global warming the tropical ocean is warmer and associated with above normal pressure in the middle to high troposphere, which suppresses the general formation of tropical cyclones, leading to greater intensities associated with the systems that do develop (Kang and Elsner 2015). This increase in tropical cyclone intensity at the expense of frequency occurs in the presence of an increase in moisture in the lower atmosphere (and therefore an increase in the convective instability of the atmosphere) associated with a warmer ocean (Kang and Elsner 2015). However, it should be noted that significant uncertainties surround the model projections in terms of the quantitative changes in the number of very intense tropical cyclones and decreases in the overall number of cyclones, globally and even more so at regional (specific ocean basin) scales. Even when comparing to present-day climate the projections for the end of the 21st century under well-developed climate change signals and several degrees of global warming, uncertainties in quantitative changes are large (e.g. Christensen et al. 2013; Tory et al. 2013). This suggests that it may be a tall order for current climate models to defensibly distinguish between the changes in tropical cyclone attributes under 1.5 °C vs. 2 °C of global warming, globally and even more so at regional scales, and indeed there is currently a complete lack of studies exploring this question.

3.3.7 Runoff and flooding

AR5 concluded that confidence is low for an increasing trend in global river discharge during the 20th century and that there is limited evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale. Additionally, AR5 also concluded that increasing trends in extreme precipitation and discharge in some catchments implies, with medium confidence, greater risks of flooding at regional scale.

There has been progress since the AR5 in identifying historical and future changes in streamflow and continental runoff. Dai (2016), using available streamflow data, shows that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the World’s 200 major rivers with negative trends outnumbering the positive ones. However, although streamflow trends are mostly statistically insignificant, they are consistent with observed regional precipitation changes. From 1950 to 2012 precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeast United States, central and northern Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia, southeastern and northwestern United States, western and eastern Canada, and in some regions of Brazil. A large part of these regional trends probably has resulted from internal multidecadal and multiyear climate variations, especially the Pacific decadal variability (PDV), the Atlantic multidecadal oscillation (AMO) and the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic GHG and aerosols are likely also important (Hidalgo et al. 2009; Gu and Adler 2013; Luo et al. 2016). Alkama et al. (2013) show an increase in runoff over South Asia, northern Europe, northern Asia and North America, and a decrease over southern Europe under the RCP 8.5 emission scenario with no significant change over Central America. Additionally over South America and Africa, there is no consensus in the sign of change. Koirala et al. (2014) show increases in projected high flows in northern high latitudes of Eurasia and North America, Asia, and eastern Africa and decreases in mean and low flows in Europe, Middle East, southwestern United States and Central America under the RCP8.5 scenario with similar spatial distribution and lower magnitude of projected changes under the RCP4.5 scenario.

Among human activities that influences the hydrological cycle are land-use/land-cover changes and water withdrawal for irrigation, which can have a big impact on runoff at basin scale although there is less agreement over its influence on global mean runoff (e.g. Gerten et al. 2008; Sterling et al. 2012; Betts et al. 2015). Some studies suggest that increases in global runoff resulting from changes in land-cover or land-use (predominantly deforestation) are counterbalanced by decreases from irrigation (Gerten et al. 2008; Sterling et al. 2012).

Most recent analysis of trends and projections in flooding and extreme runoff are limited to basin or country scales (Camilloni et al. 2013; Alfieri et al. 2015; Huang et al. 2015; Mallakpour and Villarini 2015; Aich et al. 2016; Stevens et al. 2016) with few at global or continental scales (Hirabayashi et al. 2013; Dankers et al. 2014; Asadieh et al. 2016; Dai 2016; Alfieri et al. 2017). They show regional projected changes in flooding and extreme streamflow consistent with the projected patterns in precipitation.

[TBC: Results from projections for 1.5 °C global warming, new literature is expected]

3.3.8 Snow and permafrost

3.3.9 Ocean chemistry

Changing atmospheric gas concentrations as well as ocean temperature and mixing have resulted in profound changes to ocean chemistry (Andrews et al. 2013). Around 30% of CO_2 emitted by human activities has been absorbed by the ocean where it has combined with water to create a dilute acid (ocean acidification; IPCC WG1 AR5; Cao et al. 2007). Impacts on ocean chemistry increase with further addition of CO_2 from human activities.

Increasing levels of CO_2 in the atmosphere have decreased pH of the ocean by 0.1 pH units since the Preindustrial Period, as well as having changed the concentration of key ions such as protons, carbonate and bicarbonate (Haugan and Drange 1996). Total acidity and bicarbonate ion concentrations have increased by around 30%, while carbonate concentrations have decreased by a similar amount (Cao and Caldeira 2008; AR5 WGII Box CC-OA; WGI AR5 Box 3.2; WGI AR5 Figure SM30-2).

Rates of change in ocean chemistry are already higher than that seen in the last 65 million years, if not the last 300 million years (e.g. ocean acidification; Honish et al. 2012). Periods of high atmospheric concentrations of CO_2 in the paleo-record have been accompanied by a major reduction in calcifying ecosystems such as coral reefs (e.g. KT Boundary; (Veron 2008). The time taken to reverse ocean acidification by continental weathering processes takes tens of thousands of years (Honish et al. 2012) and hence consideration must be given to the irreversibility of the emerging risks associated with changes to ocean chemistry.

Acidification of the ocean is not uniform across the ocean and is highest in areas where temperatures are lowest (Polar Regions, low temperature, increased CO_2 solubility), or near upwelling areas or areas where coastal effluents affect the chemistry of seawater (Doney et al. 2009). There is a growing number of impacts on biological systems in the ocean from these changes (Kroeker et al. 2013; Gattuso et al. 2015). Ecosystems characterized by high rates of calcium carbonate deposition (e.g., coral reefs, some plankton communities) are sensitive to decreases in the saturation states of the two forms of calcium carbon crystals (i.e. aragonite and calcite).

Other aspects of ocean chemistry have been changing. Oxygen concentrations vary regionally, and are highest at the Polar Regions, and lowest in eastern basins of the Atlantic and Pacific oceans, and in the northern Indian Ocean. Increasing temperatures in the upper layers of the ocean has led to a decrease in the solubility of gases such as oxygen with concentrations declining at the rate of 2% since 1960 (Schmidtko et al. 2017). Changes in ocean mixing together with increased metabolic rates in the deep ocean has increase the frequency of areas ('dead zones') where oxygen has fallen to levels which are unable to sustain oxygenic life (Altieri and Gedan 2015). Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures (Durack et al. 2012).

Existing risks are likely to rise steadily as atmospheric CO_2 concentrations increase (e.g. risks to fisheries and aquaculture, Alin et al. 2014, Feely et al. 2016; coastal protection provided by coral reefs; plankton communities within coastal and oceanic food webs, Mathis et al. 2015, Bednaršek et al. 2017). Risks become much greater as atmospheric CO_2 increase beyond 450 ppm, with a significant reduction in the impacts likely to ecosystems and human systems if concentrations of CO_2 are kept lower than this (Kroeker et al. 2013). Risks associated with declining oxygen have not been comprehensively assessed, and should be the focus of future research.

3.3.10 Ocean circulation and temperature (e.g., upwelling)

The temperature of the upper layers of the ocean (0-700 m) has been increasing at a rate just behind that of the warming trend for the planet. The surface of three ocean basins have been warming over the period 1950-2016 (by 0.*XX* °C, 0.*YY* °C, and 0.*ZZ* °C for the Indian, Atlantic and Pacific oceans respectively), with the greatest changes occurring at the highest latitudes (Artic - Equator: +0.*TT* °C).

Isotherms (lines of equal temperature) are traveling to higher latitudes at rates of up to 40 km per year (Burrows et al. 2014; García Molinos et al. 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (AR5 WGII Ch30). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature as well as more intense patterns of climate variability (e.g. climate change intensification of ENSO). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to the surrounding oceans under climate change, have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents) (Bakun 1990). The most authoritative studies of observed trends are indicative of a general strengthening of longshore winds (Sydeman et al. 2014), but are unclear in terms of trends detected in the upwelling currents themselves (Lluch-Cota et al. 2014). However, the weight of evidence from CGCM projections of future climate change indicates the general strengthening of the Benguela, Canary and Humboldt up-welling systems under enhanced anthropogenic forcing (Wang et al. 2015). This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, but at lower latitudes long-shore winds may decrease as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al. 2017; Engelbrecht et al. 2009 Engelbrecht et al., 2017 *in prep*). Key to analysis of the relative impact of 1.5 °C and 2 °C of global warming on upwelling systems, may be the analysis of changing land-temperature gradients for different temperature goals. Such an analysis can be performed for the large ensembles of CMIP5 CGCMs, and can be supplemented by more detailed parameterisations derived from high-resolution regional climate modelling studies (Engelbrecht et al., 2017; *in prep*).

Evidence that thermohaline circulation is slowing has been building over the past years, including the detection of the cooling of surface waters in the north Atlantic plus strong evidence that the Gulf Stream has slowed by 30% since the late 1950s. These changes have serious implications for the reduced movement of heat to many higher latitude countries.

Increasing average surface temperature to 1.5 °C will increase these risks although precise quantification of the added risk due to an additional increase to 2 °C is difficult to access. The surface layers of the ocean will continue to warm and acidify but rates will continue to vary regionally. Ocean conditions will eventually reach stability around mid-century under scenarios that represent stabilization at or below 1.5 °C.

Risk for biological and human systems in coastal and low-lying areas will escalate through changes to the intensity of storms, rapid sea level rise, and increasing vulnerability as protective ecosystems such coral reefs and mangrove forests are disrupted by changing conditions. Stabilization of ocean temperature (and planetary temperatures generally) will lead to conditions that will enable biological systems to ‘catch up’ with environmental conditions through the re-assortment of organisms and ecosystems to areas of the world most optimal in terms of their biology and ecology.

The risk of negative consequences of reduced upwelling, as well as the slowing thermohaline circulation of the ocean, increase as 1.5 °C is reached. With that comes an increasing risks of disruption to food security in many regions, along with associated changes to human well-being. These changes are very likely to influence human systems, which will also benefit from a slowing and stabilisation of ocean temperature by mid-century onward. Under these conditions of stabilisation, risks and costs associated with adaptation to climate change are significantly reduced.

3.3.11 Sea ice

3.3.12 Sea level

Projected Global Mean Sea Level (GMSL) rise is the sum of contributions from ocean heat uptake and thermal expansion; glacier and ice-sheet mass loss; and anthropogenic intervention in water storage on land. There is high confidence that sea level has been rising from the late 19th to early 20th centuries and that low rates of rise characterized the previous two millennia. It is very likely that GMSL has risen by 0.17 and 0.21 m from 1901 to 2010, and that the rate has roughly doubled during the last decade of this period and between 1920 and 1950.

It is virtually certain that GMSL will continue to rise beyond 2100. This is true of all emission scenarios including RCP2.6 so that it is probable that even strong reductions in GHG emissions will not halt this process, however it may result in a slowing of the rate of GMSL rise by the end of the century. The effect of this slowing is that the year in which a particular height above present-day seal level is inundated is shifted further into the future. Two contributors to GMSLR projections (ice sheet outflow and terrestrial water storage) were reported in the AR5 without scenario dependence because, at that time, there was insufficient scientific basis to quantify these differences. Clearly, scenario dependence is crucial in assessing the effects of strong reductions in GHG emissions on GMSLR. AR5 is therefore an insufficient basis for assessing ice-sheet outflow and terrestrial water storage, and more recent projections will need to be assessed.

Ocean heat uptake and thermal expansion is the dominant component in the AR5 assessment of ((Church et al. 2013) and contributes 0.10 to 0.18 m of 0.26 to 0.55 m total GMSL rise in scenario RCP2.6 (likely ranges, 2081-2100 relative to 1986-2005). Ocean heat uptake is the integral over time of surface heat flux, the amount of consequent thermal expansion is therefore dependent not only on the cumulative total of GHG emissions but also on the pathway of emissions. In this way, reducing emissions earlier rather than later in the century more effectively mitigates GMSL rise by thermal expansion (Zichfeld, Bouttes).

In common with most other contributors to GMSL rise, ocean heat uptake and thermal expansion continue centuries to millennia beyond the stabilization of GHG and radiative forcing (e.g Zichfeld, Bouttes). In RCP2.6, for instance, the rate of GMSLR peaks at ~2030 but only falls to half this value by the end of the century (Figure 13.11). There is some potential for nonlinear behaviour in the response of ocean heat uptake to global surface warming associated with changes in ocean circulation and deep water formation.
Mass loss from mountain glaciers and ice caps is projected to account for a likely range of 0.04 to 0.16 m GMSL rise in the AR5 assessment for RCP2.6 (from a total of 0.26 to 0.55 m 2081-2100 relative to 1986-2005). The rate at which mass is lost is projected to be fairly constant through time despite changes in global surface warming, which may represent a balance between increased warming towards the end of the century the depletion of low-elevation ice.

Glaciers have a similar integral relation to global surface warming as ocean heat uptake, and glacier contribution to GMSL is similarly unlikely to stabilize by the end of the century even under strongly reduced GHG emissions. Projections suggest that between 45 and 85% of current ice volume will survive to the end of the century (Clark et al., *XXXX*). Mass lose from marine-terminating glaciers by ice berg calving is not well represented by models and may introduce nonlinearity into the response of glaciers to climate change.

The Greenland ice sheet can contribute to GMSL rise in two main ways. These are by increases in the outflow of ice (typically by the calving of ice bergs and the melt at the termini of marine outlet glaciers) and by increases in surface melt. While projections of the latter are routinely made, process-based modelling of the former is in its infancy and AR5 projections were unable to differentiate between emission scenarios. Subsequently, Furst were able to make projections based on emission scenario using an ice-flow model forced by the regional climate model MAR (considered by Church et al. 2013to be the 'most realistic' such model). Furst et al obtain an RCP2.6 likely range of 0.02 to 0.06 m by the end of the century (relative to 2000). This is somewhat smaller than the RCP2.6 projection made by Church et al. (2013) (0.04 to 0.10 m) probably reflecting an over estimate of the scenario-independent contribution from outflow ('rapid dynamics').

Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Two definitions have been proposed for the threshold at which this loss is initiated. The first is based on the surface temperature at which net Surface Mass Balance (SMB, the difference between mass loss, mostly melt and subsequent runoff, and gain, mostly snowfall) first becomes negative for the current ice-sheet geometry. Church et al. (2013) assess this threshold to be 2 °C or above (relative to pre-industrial). A second definition is based on the evolution of a dynamical model of the ice sheet when forced in an ensemble of prescribed warmings. Robinson et al. (*XXXX*) find a very likely range for this threshold of 0.8 to 3.2 °C. In both cases, the timescale for eventual loss of the ice sheet can be tens of millennia and assumes constant surface temperature forcing during this period. Were temperature to cool subsequently, the ice sheet may regrow although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat.

Published process-model projections are now available for the contribution of the Antarctic ice sheet to GMSL rise over the remainder of the century, which are based on models that could potentially allow Marine Ice Sheet Instability (MISI, the continued retreat an ice sheet resting on bedrock below sea level once triggered by external warming of the surrounding ocean and/or atmosphere) so that the separate assessment of MISI used by Church et al. (2013) may no longer be necessary.

The three main papers to provide projections can be divided into two groups. De Conto and Pollard (*XXXX*) and Golledge et al. (*XXXX*) both suggest that RCP2.6 is the only RCP scenario leading to millennial-scale contributions to sea level of below 1 m, and de Conto and Pollard (*XXXX*) indicate a contribution to GMSL rise of 0 to 0.22 m by the end of the century. Cornford et al. compared SRES scenarios A1B and E1 (emissions stabilized at 500 ppm CO_2 by 2050). They obtained the counter-intuitive result of a higher contribution to sea level from E1 than A1B of ~0.02 m by the end of the century. This arises because ocean warming in both A1B and E1 is similar and generates similar increases in outflow, however increases in snow fall caused by atmospheric warming (e.g., Clark et al.) are greater in A1B which compensates the increased outflow and leads to a reduced contribution to GMSL rise. The difference between these two set of projections can most likely be attributed to both the numerical treatment of grounding-line migration (e.g., Durand and Pattyn) and detailed forcing employed (Cornford used results from regional atmosphere and ocean modelling, including Helmer et al.). De Conto and Pollard (*XXXX*) introduce a new mechanism by which ice can be lost rapidly from Antarctica (cliff collapse), however amount of surface warming required to initiate this process seems very unlikely for reduced emission scenarios, such as RCP2.6. Levermann et al. (*XXXX*) develop response functions for the ice sheet based on the idealised SEARISE inter-comparison (Bindschadler et al.) and obtain an end-of-century projection of 0.02 to 0.14 m for RCP2.6. Both the long-term committed future of Antarctica and its end-of-century GMSL contribution are complex and require detailed process-based modelling, however a threshold in this contribution may be present close to scenario RC2.6.

There is potential for the methodology used by Church et al. (2013) to derive GMSL rise projections to be used in the present special report with updated process-based projections for the individual contributors based on RCP2.6 and using recent literature published after AR5, in particular for the Greenland and Antarctic ice sheets.

Church et al. (2013) indicate that it is very likely that sea level will have a strong regional pattern through the 21st century and beyond, however it is also very likely that over about 95% of the world's ocean will experience sea level rise and that about 70% of global coastlines will experience sea level rise within 20% of the global mean. While Church et al. (2013) are primarily concerned with RCPs 4.5 and 8.5, it seems probable that these statements also apply to RCP2.6 and scenarios in which emissions are strongly reduced. It is also very likely that there will be an increase in extreme sea levels by 2100 in some regions because of increased mean sea level (*high confidence*) and storms (*low confidence*). Assuming that the former is the main driver of extreme sea levels, a technique based on a network of the tide gauges covering most of the world (Hunter *XXXX*) could be used to assess differences in return period associated with emissions scenarios close to RCP2.6, as it was for RCP4.5 in Church et al.

3.3.13 Identified hot spots based on regional climate changes and associated hazards.

3.4 Observed impacts and projected risks in natural and managed ecosystems

3.4.1 Introduction

The natural and managed ecosystems assessed in the Working Group II contribution to the IPCC AR5 were freshwater resources; terrestrial and inland water systems (in this report now called terrestrial and wetland ecosystems), coastal systems and low-lying areas, ocean systems, and food security and food production systems. Natural and managed ecosystems are embedded within the reasons for concern / key vulnerabilities assessed within the context of Article 2 of the UNFCCC (Cramer et al. 2014) and included the following key risks which pertain to the systems covered in this:

- Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise;
- Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings;
- Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic; and
- Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.

3.4.2 Terrestrial and wetland ecosystems

3.4.2.1 Observed impacts

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis (AR5-WGII Chapter 4).

The literature assessed in the AR5 typically focused on describing and quantifying linkages between weather and climate patterns and outcomes, with limited detection and attribution studies (Cramer et al. 2015). The observed changes described in this section contribute to the loss of ecosystem services (e.g. access to safe water) that are supported by biodiversity (Cramer et al. 2014) and hence contribute to the risks assessed in section 3.5.

3.4.2.1.1 Palaeoecological evidence

The paleoecological records provide high confidence that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions (Lorenzen et al. 2011). Most of the world regions have known a significant land use after 250 years BP, except Europe, Mediterranean Basin, Asia, Central America where significant changes occurred 1000 to 3000 years ago (Ellis et al. 2013).

The regional annual mean warming during the Holocene was about 0.5 °C to 1.5 °C above preindustrial in some continental-scale regions (AR5-WGII Chapter 4). In some regions (NW Europe, East Canada, south Africa) the warming largely passed the +2 °C and even +3 °C, but in others, it is rather a cooling (Mediterranean, west North America) (Bartlein et al. 2011). So, the direct analogy with the paleoecological record is unwarranted because past climatic changes were not global and because future climate change will interact with other global changes such as land use change, invasive species, pollution, and overexploitation of natural resources, which are projected to be more intense in the future. The paleoecological record and models provide high confidence that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2 °C to 3 °C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Armsworth et al. 2015).

Paleoecology may also help to throw light on species extinction. So the St Paul Island in Alaska mammoth seemed to extinct because of the synergistic effects of shrinking island area (due to sea-level rising) and freshwater scarcity due to climate change in mid-Holocene (Graham et al. 2016). This is confirmed for the Mediterranean Islands (Médail 2017). This illustrates the vulnerability of small island populations to environmental change, even in the absence of human influence.

3.4.2.1.2 Global overview of impacts on major ecosystem components and functions

The vulnerability of ecosystems to climate change is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. The absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century for 2 °C+ global warming scenarios; ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (Jones et al., 2009) (AR5-WGII-chap4).

Phenology:

A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007). A global review by Parmesan and Hanley (2015) confirms this fact for 72% of the species, but they highlight that the response is often more complex and need community-level experiments. For plants, remote sensing studies show that, between 30°N and 80°N, the start of growing season significantly advanced, while the growing season end was delayed (Jeong et al., 2011). It is confirmed for some regions (Wu et al. 2016; Dugarsuren and Lin 2016; Crabbe et al. 2016) but not everywhere (Zhang et al. 2016; Liu et al. 2016). Keenan and Richardson (2015 Global Ch Biol) showed that, for US tree species, the timing autumn senescence is significantly correlated with timing of spring bud burst, more than autumn temperature, confirming the key role of the spring phenology for future climate change impact. For animals, although a number of non-climatic influence phenology, warming has contributed to the overall spring advancement observed in the NH (high agreement and medium evidence, AR5 Section 4.3.2.1.2, p292). A global synthesis for trout (Kovach et al. 2016) shows that the changes in hydrology are more important for trout demography and growth that changes in temperature.

Since 1985, timing of phenological spring, summer and autumn in Harbin, Heilongjiang Province of China have been advanced by 7 days, 6 days and 19 days respectively, while timing of phenological winter has been delayed by 2 days. Temperature changes before the majority of phenophases is probably the main reason for the changes of phenological season during 1985-2012 (Xu et al. 2015).

Primary productivity:

Primary production is fundamental to the global carbon cycle and underpins provisioning ecosystem services such as food, timber, and grazing. According to AR5-Chap4, there is high confidence that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is low confidence in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution. From a meta-analysis covering all ecosystems, Slot and Kitajima (2015) found that leaf respiration of most terrestrial plants can acclimate to gradual warming, potentially reducing the magnitude of the positive feedback between climate and the carbon cycle in a warming world. After a typhoon (which are projected to be more frequent and more intense), the soil is enriched with organic matter and nutrients for several months, which provide better conditions for the spread of fast-growing species (Wang et al. 2016).

Biomass and carbon stocks:

Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (high confidence) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century. In the tropical regions, Anderegg et al. (2015) show that the interannual variability of global land C sink has grown by 50-100% over the past 50 years and that interannual land C sink variability is most strongly linked to tropical nighttime warming, likely through respiration. Spring warming has largely stimulated ecosystem productivity at latitudes between 30 degrees and 90 degrees N, but suppressed productivity in other regions (Xia et al. 2014). The analysis of long-term forest dynamics research sites (CTFS-ForestGEO) shows a significant aboveground biomass increase and a positive trend in abundance of lianas in the tropical forests between 2000 and 2012 (Anderson-Teixeira et al. 2015). From 1901 to 2010, Fisher et al (2015) assess from nine land surface models that the African rain forest was an increased sink of carbon but with also an increasing uncertainty. A green effect due to fertilization is often observed in the tropics (Murray-Tortarolo et al. 2016; Zhu et al. 2016). Yang et al. (2015) show a significant upward trend between the mid-1980s and the 2000s as a result of more frequent fires in ecosystems with high carbon storage, such as peatlands and tropical forests (reduction of the carbon sink of global terrestrial ecosystems by 0.57 PgC/yr. Lal (2014, Soil Carbon) highlights the promise of soil C sequestration on the basis of the magnitude of net biome productivity (3 Pg C/year), and the hypothesis that some of this productivity can be retained in the soil to offset emissions and also enhance the resilience of soil and agroecosystems to climate change. (Munoz-Rojas et al. 2016) demonstrated increased rates of soil respiration in semi-arid ecosystems in burnt areas versus unburnt ones.

Evapotranspiration and water use efficiency: Summary from AR5

AR5 Chapter 4 concluded that there has been no significant evapotranspiration trend since approximately 2000, possibly due to soil moisture limitation and that intrinsic water use efficiency (iWUE) increased since preindustrial times (1850 or before) at several forest and grassland sites (Penuelas et al., 2011; (Silva and Anand 2013) but iWUE decreased by 30% between 1950 and 2014 in phosphorus limited subtropical forests (Huang et al, 2015; New Phyt). Remote-sensing data reveals that land-cover and land-use change in recent years has led to a decline in global water use efficiency Tang et al. (2014). Mediterranean summertime ecosystem WUE was about 66% higher during Mistral northerly wind than other days, so that the historical decrease of Mistral frequency in Sardinia reduced the estimated summertime WUE by 30% (Montaldo and Oren 2016).

Changes in species range, abundance and extinction:

AR5 Chapter 4 concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming. Uncertainties concerning attribution to climatic change remain important. Responses at the “trailing edge” of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the “leading edge” (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes and difficulties in detecting local extinction with confidence (Thomas et al., 2006). Average range shifts across taxa and regions were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. In the tropics, habitat loss and land-use change had the largest impact on species richness, whereas in the boreal forest and Northern temperate forests, species invasions had the largest impact on species richness (Murphy and Romanuk 2014).

Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN) in its red list, only 20 have been tenuously linked to recent climate change (Cahill et al., 2013). Using the same red list, Taylor and Kumar (2016, Trop Conserv Sc) have investigated literature for terrestrial vertebrate and vascular plant species, in the Pacific Islands, and found that on 305 species, 42 were near threatened, 78 were vulnerable, 44 were endangered, and 34 were critically endangered. This is confirmed by Wiens (2016) who found 47% of local extinctions, especially in tropical regions, in animals (relative to plants), and in freshwater habitats. The extinction of the Bramble Cay Melomys in the Torres Strait has been attributed as likely due to climate-change induced increases in storm surges and sea level rise which have led to habitat destruction (Gynther, I., Waller, N. & Leung 2016) see also Section 3.3.6 where observed changes in storm surges are discussed).

3.4.2.1.3 Observed impacts on major regions and ecosystem types

Regions that exhibit relatively high projected temperature changes (often greater than the global mean by 50% or more) are high-latitude Northern Hemisphere land areas and the Arctic, especially in December–January–February, and Central North America, portions of the Amazon, the Mediterranean, and Central Asia in June–July–August (AR5 Chapter 4, p. 1159). Precipitation patterns are much more heterogeneous, but semi-arid and arid regions know decrease of precipitation (winter in North Africa, spring in East Africa, austral summer in south Africa, low to medium confidence).

Regional impacts – Summary from AR5

WGII AR5 noted that the observed impacts of climate change on terrestrial ecosystems are particularly pronounced:

- In Africa with emerging evidence on shifting ranges of some species and decrease of water resources (with impact on the agriculture) particularly due to elevated carbon dioxide, climate change beyond the effects of land use change and other non-climate stressors (high confidence)
- In Europe, effects are measurable on the distribution, phenology, and abundance of animal, fish, and plant species (high confidence)
- In many parts of Asia, terrestrial systems have responded to recent climate change with shifts in the phenologies, growth rates, and the distributions of plant species, and with permafrost degradation (high confidence)
- In Australasia, recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (very high confidence).
- North American ecosystems are under increasing stress from rising temperatures, carbon dioxide (CO2) concentrations, and sea levels, and are particularly vulnerable to climate extremes (very high confidence)
- In some areas of Antarctica and the Arctic, impacts on terrestrial and freshwater ecosystems are due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*).

New literature confirms these findings or attributes additional changes in terrestrial ecosystems in tropical regions: NPP decrease associated to dryness (Shufen et al. 2015), recent increase of sink of carbon in rain forests (Fisher et al, 2015), but decrease sink after forest fires Yang et al. (2015), increase of species extinctions and endangering (Wiens 2016). In the arctic ecosystems, (Mortensen et al. 2014) (2015; Pol Biol) indicate that among the 114 abiotic, performance and phenological variables related to several tens of taxa, 32 showed a positive trend and 51 a negative trend, the most negative concerning the plants, arthropods, predators, zooplankton. Cooper (2014; An Rev Ecol Evol Syst) show that (1) delays in winter onset affect tundra carbon balance, faunal hibernation, and migration but are unlikely to lengthen the plant growing season, (2) mild periods in winter followed by a return to freezing have negative consequences for plants and invertebrates. Long-term absence of snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-Werry et al, 2016). In very man disturbed ecosystems, such in China or Ethiopia, the attribution to climate change is more difficult: China (Xu et al. 2016; Piao et al., 2015 Glob Ch Biol; Jacob et al. 2015). In semi-arid biomes of the SW USA, recent drought conditions had a strong negative impact on vegetation production (Barnes et al. 2016).

Seddon et al. (2016) quantitatively measured ecologically sensitive regions with recent amplified responses to climate variability in the Arctic tundra, parts of the boreal forest belt, the tropical rainforest, alpine regions worldwide, steppe and prairie regions of central Asia and North and South America, the Caatinga deciduous forest in eastern South America, and eastern areas of Australia.

63% of vegetation in Central Asia during the period 1982–2012 was found to be significantly affected by precipitation ($p < 0.05$) while 32% vegetation was affected by air temperature ($p < 0.05$). The spatial patterns of the normalized difference vegetation index (NDVI) variations in Central Asia were consistent with the spatial patterns of precipitation variations. However, the temperature responses of vegetation NDVI differed across the northeast and the mountainous regions in Central Asia (Zhang et al. 2016).

Forest and Woodlands – Summary from AR5

WGII AR5 concluded that deforestation has slowed over the last decade, including in the tropical regions. Nevertheless, the carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change due mostly to tropical deforestation and forest degradation. Boreal forest productivity has increased as a result of warming (*medium confidence*) during the 1980s but many areas have experienced productivity decline (*high confidence*) because of drying air and lack of adaptation. The world's temperate forests act as an important carbon sink (robust evidence and high agreement), representing 65% of the global net forest carbon sink. Moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods (*medium evidence*, *high agreement*). Keenan (2015) did a review of literature on climate change impacts in forest management. He found that 76% of 1172 papers involved assessment of climate change impacts or the sensitivity or vulnerability of forests to climate change. Laurance (2015, Ann Miss. Bot Garden) highlights that tropical forest mainly threatened until now by industrial exploitation and human population growth is now also threatened by climatic change and many species are harmed by emerging pathogens. All the dangers often operate in concert. Shestakova et al. (2016 PNAS) demonstrate how an intensified climatic influence on tree growth during the last 120 years has increased spatial synchrony in annual ring-width patterns within contrasting (boreal and Mediterranean) Eurasian biomes and on broad spatial scales.

Dryland ecosystems: Savannas, shrublands, grasslands, deserts – summary from AR5

According to WGII Chapter 4, in many places around the world the savanna boundary is moving into former grasslands on elevation gradients and tree cover and biomass has increased over the past century. It has been attributed to changes in land management, rising CO_2, climate variability and change (often in combination). Rangelands are highly responsive to changes in water balance. For the Mediterranean species, it has been observed shift in phenology, range contraction, health decline because of precipitation decrease and temperature increase. Tropical fish Geophagus brasiliensis introduced in southwestern Australia river from South America has a growth rate higher than most of the native fish species (Beatty et al., 2013, Aq Inv). The area percentage of actual grassland NPP change on Tibet Plateau caused by climate change strongly declined over the last 30 years, but the percentage change resulting from human activities doubled in the same periods Chen et al. (2014). Guan et al. (2014; JGR) found that the rainy season length has strong nonlinear impacts on tree fractional cover of dry forests and savannas.

Rivers, lakes, wetlands, peatlands: summary from AR5

According to WGII Chapter 4, freshwater ecosystems are considered to be among the most threatened on the planet. Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg). They are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning. Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is currently occurring at an unprecedented rate and geographic scale (Herbert et al. 2015).

The ecosystem water conservation (EWC) of the alpine ecosystem of the Source Region of the Yellow River (SRYR) has a slightly decreasing trend of -1.15 mm/a during the period of 1981-2010.In the southeast of the SRYR with sub-humid climate, both decreased precipitation and increased potential evapotranspiration induce the significant negative changes in the EWC. Meanwhile, in the northern part with semi- arid climate, increased precipitation is the main climatic factor leading the EWC to increase (Yunhe et al. 2016).

Tundra, alpine and permafrost systems

According to WGII Chapter 4, the High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century, with an increased vegetation productivity in both North America and northern Eurasia. The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. This is confirmed by recent literature (Bring et al. 2016; Yang et al. 2016; Jiang et al. 2016 DeBeer et al. 2016 HydroEarthSysSc). Both of these processes facilitate conditions for woody species establishment in tundra areas. There is medium confidence that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number

(Vongraven and Richardson, 2011).

3.4.2.2 Projected risks and potential adaptation (including limits)

3.4.2.2.1 Global overview of projected risks to major ecosystem components and functions

The focus of this section is to compare projected risks to terrestrial and wetland ecosystems at 2 versus 1.5 ºC warming. However, the outcomes of emission reduction strategies (in terms of projected global warming) are probabilistic: therefore, the benefit of a mitigation strategy aimed at constraining warming to 1.5 ºC is also a greatly reduced chance to incur the risks associated with 4 ºC warming

Biome Shifts: Summary from AR5

Using an ensemble of seven Dynamic Vegetation Models driven by projected climates from 21 alternative Global Circulation Models, Warszawski et al. (2013) show that approximately 25% more biome shifts are projected to occur under 2 °C warming than under 1.5 °C warming (Figure 3). The proportion of biome shifts is projected to (approximately) further double for warming of 3 °C. This is consistent with an earlier study which projected 1.6 °C warming would induce a 10% transformation of global ecosystems (47% wooded tundra, 23% cool conifer forest, 21% scrubland, 15% grassland/steppe, 14% savannah, 13% tundra and 12% temperate deciduous forest, with ecosystems variously losing 2–47% of their extent).

Changes in species range, abundance and extinction: Summary from AR5

Fischlin *et al* 2009 (AR4 Chapter 3) estimated that 20-30% of species would be at increasingly high risk of extinction if global temperature rise exceeds 2-3 °C above pre-industrial levels. (Settele et al. 2014) also mentioned these risks. Warren et al. (2013) simulated climatic range loss for 50,000 species using 21 alternative projected climates derived from GCM output, and projected that with 4 °C warming, and realistic dispersal rates, 34+/-7% of the animals, and 57+/-6% of the plants, would lose 50% or more of their climatic range by the 2080s. In comparison, with 2 °C warming these projected losses were reduced by 60% if warming were constrained to 2 °C.

Settele et al. (2014) state that large magnitudes of climate change will 'reduce the populations and viability of species with spatially restricted populations, such as those confined to isolated habitats and mountains'.

A recent update to Warren et al. (2013) incorporating 80,000 species is included in (Smith *et al.* in prep) explores the outcome for 2 versus 1.5 °C warming. At 2 °C, 15+/-3% animals and 19+/-3% plants are projected to lose 50% or more of their climatic range, whilst at 1.5 °C warming this falls to 7+/-2% animals and 9+/-2% plants. Constraining warming to 1.5 °C thus avoids approximately 53% of the impacts that would otherwise occur at 2 °C warming. The study also identifies areas where at least 75% of species currently present (and included in the simulations) can remain under a changed climate. It finds that the increase in the area of climatic refugia for plants (under 1.5 ºC vs. 2 ºC) is equivalent in size to the current global protected area network overall. These benefits accrue in the absence of temperature overshoot – if overshoot occurs, for example to, these benefits would be reduced or even negated, depending on the length of time of the overshoot (Smith *et al.* in prep).

Biomass and carbon stocks: Summary from AR5

Irreversible regional scale change: Summary from AR5

A 'high risk the large magnitudes and high rates of change will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon and the Arctic' was identified (Settele et al. 2014).

Invasive species: Summary from AR5,

Constraining warming to 1.5 °C would significantly reduce the risk associated with the spread of invasive species, for example those that can be agricultural pests or cause disease in animals (examples from Australia include Queensland fruit fly, chytridiomycosis in frogs, Box 25.4, Reisinger et al. 2014)

Limits to adaptation: Summary from AR5

Oppenheimer et al. (2014) (AR4 Chapter 19) project that unique and threatened systems would be unable to adapt to levels of warming exceeding 2 ºC. Settele et al. (2014) summarise how rates of climate change also affect the ability of terrestrial ecosystems to adapt, and show how many species will be unable to track suitable climates under mid and high rates of warming during the 21st century. Constraining warming to 1.5 ºC within this century, without an overshoot, would also reduce the rates of warming, increasing the potential for these species to track their climate space and for unique ecosystems to adapt. It will also allow more time for conservation management strategies to be enhanced to allow for changing climates (Warren et al.) *submitted*)

3.4.2.2.2 Projected risks to major regions and ecosystem types

Regional Risks

Projected risks exist for all geographical regions for warming of 1.5 °C or 2 ºC. However, projected biome shifts are already extremely severe in the Artic and in alpine regions at 1.5 ºC warming and increase further for 2 ºC warming (Gerten et al. 2013 Figure 1b,). Island biodiversity is also projected to be at risk.

Forest and Woodlands

Projected impacts on forests including increases in the intensity of storms, wildfires and pest outbreaks were also highlighted (Settele et al. 2014), potentially leading to forest dieback. Romero-Lankao et al. 2014 (Box 26-1) indicate significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5 ºC than at 2 °C).

Dryland ecosystems: Savannas, shrublands, grasslands, deserts

Mediterranean-type ecosystems were identified as being particularly sensitive to climate change in both Fischlin *et al.* 2007 and Settele et al. 2014, being vulnerable to drought and increased fire frequency. Recent studies using independent complementary approaches now show that there is a regional-scale tipping point in the Mediterranean between 1.5 °C and 2 ºC warming (Schleussner et al. 2016b; Guiot and Cramer 2016b). Using a large ensemble of climate and hydrological model projections the former identifies that at 1.5 ºC warming, median water availability is projected to decline by 9% relative to the period 1986-2005 (by which time warming of 0.6 °C above pre-industrial levels had occurred, see IPCC 2013) in comparison to 17% at 2 ºC, whilst the length of dry spells increases by 7% under 1.5 ºC warming compared to 11% under 2 °C warming. The latter finds that only 1.5 ºC warming constrains the region's climate to lie within Holocene climate variability – whilst 2 ºC warming results in transformation of 12-15% of the Mediterranean biome area. 4 ºC warming is projected to transform Southern Spain into a desert.

Song et al. (2016) examined the photosynthetic responses of *Stipa baicalensis* to relative long-term exposure (42 days) to the predicted elevated temperature and water availability changes. The elevated temperature (+4 °C) and partial irrigation reduced the net photosynthetic rate, and the reduction in Vcmax increased with increasing temperature. Although climate warming (+4 °C) caused reductions in the light use efficiency and photosynthetic rate, a self-photoprotection mechanism in *Stipa baicalensis* resulted in its high ability to maintain normal live activities.

Lü et al. (2016) pointed out that warming and changing precipitation had significant interactive effects, different from the accumulation of single-factor effects, on functional traits of Stipa species. The correlation and sensitivity of different plant functional traits to temperature and precipitation differed. Precipitation is the key factor determining the growth and changes in plant functional traits in Stipa species, and that temperature mainly influences the quantitative fluctuations of the changes in functional traits.

Sui and Zhou (2013) found that the regional temperate grasslands in China acted as a small carbon sink at 11.25 g C m^{-2} $year^{-1}$ in the study area of 64.96 million hectares with a high inter-annual variability ranging from -124 to 122.7 g C m^{-2} $year^{-1}$ during the period of 1951-2007. The sink of temperate grasslands will be reduced if the climate gets warmer and drier during this century since the increasing net primary production does not keep up with the increase of heterotrophic respiration.

Rivers, lakes, wetlands, peatlands:
Settele et al. (2014) find that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality.

Tundra, alpine and permafrost systems

3.4.3 Coastal and low lying areas (inc. small islands)

3.4.3.1 Observed impacts

3.4.3.2 Projected impacts

3.4.4 Ocean systems including coral reefs

3.4.4.1 Observed impacts

3.4.4.1.1 Background

Around 71% of the Earth's surface is covered by an ocean that is a critical component of the Earth's climate system (AR5 WGI Ch3). Not only does the ocean play a dominant role in maintaining stable global temperatures, climates and atmospheric gas content, but the ocean is home to vast number of organisms and ecosystems which provide ecosystem goods and services that are worth trillions of dollars ($US) each year (BCG 2016). Many of the most disadvantaged communities depend on the ocean for food and income, with inequities projected to increase as coastal and ocean resources deteriorate under the influence of climate change and other human pressures (Spalding et al. 2014).

Due to the difficulty of accessing the ocean, knowledge about the ocean and its ecosystems lags that of terrestrial ecosystems, especially when it comes to the impacts of rising atmospheric greenhouse gas concentrations on ocean habitats, ecosystems and human users. Knowledge of basic ocean systems, as well as threats and challenges, have increased significantly over the past decade. The world's largest habitat, the deep sea, remains one of the least understood on the planet, despite the fact that there is increasing evidence that's changes in the deep ocean are potentially momentous within the Earth's climate system. Understanding the components, processes, and tipping points, as well as how humans are changing this vast part of the earth is likely to become increasingly important.

3.4.4.1.2 Impacts arising from rising ocean temperatures

Ocean organisms and ecosystems are very sensitive to changes in temperature that differ from those to which they have adapted to over evolutionary time. Increased temperatures can influence physiological processes such as respiration, photosynthesis, gas exchange, and calcification, with the rate of these processes rising with temperature until a threshold level is attained, at which time rates of most physiological processes will decline rapidly (Portner et al. 2014). While there is some understanding of physiological and ecological thresholds, more work needs to be done to understand how, why and when thresholds are likely to occur. These responses to temperature can drive significant changes in organisms and ecosystems that include changes to community composition, food webs and ecosystem dynamics (Hoegh-Guldberg et al. 2014; Gattuso et al. 2015).

Organisms from phytoplankton to sharks are moving to higher latitudes as they warm, with implications for biodiversity, food webs, and ecosystem structure, with the implication that biodiversity will decrease at the equator and will increase at higher latitudes (Poloczanska et al. 2013). In other cases, responses to temperature can be abrupt, with ecosystems such as coral reefs, kelp forests and seagrass beds undergoing fundamental and sudden shifts in state (e.g. mass mortality events) at specific threshold temperatures. Threshold temperatures for many tropical organisms and ecosystems usually sit around 1 ^{o}C above the long-term summer maxima (relative to the period 1986-1992). Warming of the global ocean increases the frequency and extent to which these thresholds are exceeded.

Recent intensification of ecological impacts such as mass coral bleaching and mortality (and similarly, the progressive loss of kelp forests and other marine ecosystems) suggests that even attaining a long-term goal of an average global temperature that does not exceed 1.5 °C will still result in up to 90% of these important ecosystems disappearing over the next few decades (Frieler et al. 2012; AR5 WGII Ch30). As global temperatures rise from 1 °C to 1.5 °C above the preindustrial period, the risks of negative outcomes of these changes increase, with implications for ecosystem services such as fisheries, tourism, cultural values, and coastal protection. The exceptional warming of 2016 led to 20% of corals dying on the Great Barrier Reef (Hughes et al. 2017), with probably similar yet unmeasured amounts of change in many other coral reef systems.

Coral reefs provide important insights into the sensitivity of marine ecosystems, with considerable evidence that the additional 0.5 °C in temperature to 1.5 °C drives a further loss of 90% of reef-building corals (Hoegh-Guldberg 1999, Donner et al. 2006, Frieler et al. 2013). These changes strongly suggest that reducing non-climate stresses on coral reefs will be important to ensure that come corals survive until stabilisation around mid-century.

3.4.4.1.3 Impacts from changing ocean chemistry

Changes in ocean chemistry have the potential to cause profound effects on the biology and ecology of the ocean. While impacts such as mass fish kills from declining oxygen in the deep ocean are episodic, other impacts (ocean acidification) tend to occur gradually over time. Sub-chronic effects of changing ocean chemistry include ocean acidification influencing physiological processes such as calcification and decalcification, reproduction and development, growth, and primary productivity leading to significant changes in ecosystem structure and function (Portner et al. 2014; Kroecker et al. 2013). Given the importance of protons, oxygen, carbonate and bicarbonate ions to the biology of the sea, changing ocean chemistry comes with inherent risks for organisms, food webs and ecosystems within the ocean, and hence communities and industries (Gattuso et al. 2015).

Physiological responses to changing ocean chemistry (e.g. reduced calcification) lead to important ecological impacts (e.g. reduced reef growth, maintenance and hence shoreline protection) which are likely to, although profound, occur gradually (Dove et al. 2013). Impacts of changing ocean chemistry, therefore, despite their often-profound nature, are unlikely to produce sudden shifts in ocean ecosystems (with the exception of mass mortality events driven by more frequent and pervasive dead zones).

Given this, impacts from changes in ocean are likely to grow in size as the world travels from today's atmospheric carbon dioxide concentration (405 ppm) to those associated an average global surface temperature of 1.5 °C. The increase of concentrations of CO_2 to those associated with 2 °C and higher (> 450-500 ppm) will become increasing influential, with an increasing risk of fundamental and potentially irreversible negative changes across a broad scope of physiological and ecological processes. Changes in ocean chemistry and the impacts on biology are affecting industry (e.g. dead zones and fish kills => fisheries; changing ocean pH => coastal aquaculture: Feely et al.). While the consequences for human systems is poorly known, irreversibility plus the fundamental nature of these changes poses significant risks for the future.

3.4.4.1.4 Other climate change drivers

Increased sea temperatures are driving more intense storm systems, although the frequency of storms overall is not increasing. Intensifying storm systems are also contributing and increased frequency of destructive events which are impacting ecosystems such as coral reefs through the breakage of corals and the souring effects of waves and storm surge (De'ath et al. 2012). Other coastal ecosystems may be similarly affected by storms surge and waves (e.g. mangroves, seagrass). Sea level rise in low-lying and coastal areas are already changing the distribution of coastal vegetation, with ecosystems like mangroves and salt marsh moving landward as coastal areas flood.

Other factors such as changes to inundation present additional risks by changing the quality of coastal water quality through sediment and nutrients mobilized as part of an intensified drought-flood cycle. These threats are exacerbated by human activities such as coastal deforestation and farming methods that lead to increased erosion in the catchments of coastal rivers.

3.4.4.1.5 Impacts on fisheries

As discussed above, the distribution and potential catches of marine fishes and invertebrates are affected by changes in ecosystem drivers, including temperature, oxygen level, acidity and net primary production that scale with atmospheric warming (and thus cumulative carbon emission). Globally, sea surface changes in ecosystem system drivers are projected to scale linearly with atmospheric warming (from 0 °C to 4 °C) while sub-surface changes are more non-linear (*possible Figure 1* – projected scaling between atmospheric warming and ecosystem drivers, including surface and bottom, by ocean regions);

Impacts on marine fish stocks and fisheries are lower in 1.5-2 °C global warming relative to pre-industrial level when compared to higher warming scenarios (*possible Figure 2* - scaling of observed and projected impacts between impact indicators and atmospheric warming). Sensitivity to the 1.5-2 °C relative to other warming scenarios differ between regions, with fish stocks and fisheries being highly sensitivity in tropical and polar systems.

Direct benefits of achieving the 1.5 °C global warming target can be substantial from increases in fisheries revenues and contribution to protein and micronutrients availability particularly to the most vulnerable coastal communities (tropical developing countries and SIDS) (*possible Figure 3* – maps of change in potential catches and revenues, with vulnerable countries highlighted).

3.4.4.2 Projected risks and adaptation options

Non-climate factors can play important roles by interacting, exacerbating and dampening impacts related to climate change. Separating out the individual effects of climate change stressors such as those associated with increasing temperature versus ocean acidification is difficult or impossible given the complex ways that they interact, synergistically and / or antagonistically. Given the role that some non-climate stresses play in determining the resilience of biological systems in response to climate change, reducing non-climate change related factors has potential to reduce the risk and outcome of climate change related impacts.

Other impacts include those stemming from the combined impacts of intensifying storms, sea level rise, and other non-climate change related stresses (e.g. pollution, coastal development). Reducing the stress of non-climate factors has potential to reduce the impact of climate change in some cases, and buy important time while the international community restrains emissions such that average global temperature will the maintained well below 2 °C and 1.5 °C and the long-term.

Stabilization of ocean temperature by mid-century is an important characteristic of the 1.5 °C trajectory (RCP1.9 and RCP2.6) in that it enables biological and human systems to adapt and eventually re-establish vibrant and productive marine ecosystems. Adapting to further change in average global surface temperature of 0.5 °C will require considerable investment and time. However, investments are likely to be returned through the benefits of resilient ecosystems, industries and communities.

The increasing stability of ocean environments also has longer term benefits in terms of enabling genetic adaptation to occur through the redistribution of genotypes to new locations where stable conditions match those that the organisms have been adapted to, or where evolution has had enough time to take place. In each case, the length of time involved is likely to be long (i.e. decades to centuries).

Industries are likely to be less affected with significant savings if the 1.5 ºC target is achieved. Scope of risk-reduction through adaptation through improved fisheries management, habitat restoration / enhancement and / or diversification of sources of food and livelihood increases substantially with under the 1.5 ºC.

To achieve 1.5 ºC Celsius global warming target, negative mitigation measures may alter pattern of ocean biogeochemistry and primary productivity, and increase intensity of changes in ecosystem stressors in some regions (e.g. lower oxygen level in deeper waters) which impacts fish stocks and fisheries. In contrast, nature-based solutions such as blue carbon may generally have co-benefits in enhancing fish stocks and fisheries.

Potential non-linearity scaling of sub-surface ecosystem drivers and the resulting effects on fish and fisheries implies that carbon mitigation pathways with bigger overshoot to achieve 1.5 °C by the end of the 21st century may have higher impacts.

3.4.5 Freshwater Resources (quantity and quality)

3.4.5.1 Observed impacts

Detection and attribution to freshwater resources including quantity and quality must be interpreted with caution because of confounding factors such as land use changes, water demand, and urbanization (AR5-WGII Chapter 3).

3.4.5.1.1 Stream flow

Summary from AR5

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (robust evidence, high agreement) and has increased winter flows because more winter precipitation falls as rain instead of snow. There is robust evidence of earlier breakup of river ice in Arctic rivers. Streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (AR5-WGII Chapter 3).

New information since AR5:

The number of studies on detection and attribution of observed changes in streamflow has been increasing since AR5. In the studies, multiple drivers such as land use change, urbanization, reservoir control, water consumption and the significant natural variability of hydrological variables are considered. For example, anthropogenic influence had a far greater contribution (>56.6%) to the streamflow variability than that by climate change (<43.4%) in the Liao River Basin, one of the largest basins in northeast China (Jiang and Wang, 2016).

[Add more quantitative information in the FOD]

3.4.5.1.2 Groundwater

Summary from AR5

Attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult owing to additional influences of land use changes and groundwater abstractions (Stoll et al., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare owing to a lack of appropriate observation wells and a small number of studies. (AR5 WGII Chapter 3)

New information since AR5

Since AR5, the number of studies based on long-term observed data has been limited. For example, the groundwater-fed lakes in north-eastern central Europe have been affected by climate and land use changes and show a predominantly negative lake-level trend in 1999–2008 (Kaiser *et al.*, 2014).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.3 Water quality

Summary from AR5

Most observed changes of water quality due to climate change are known from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables. Even though some studies extend over as many as 80 years, most are short term. The linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime, and the many other possible sources of pollution (high confidence, AR5 WGII Chapter 3).

New information since AR5

Regional studies that have been conducted since AR5 demonstrate the water temperature increase and water quality degradation by climate change. For example, the mean yearly temperature of fluvial waters over the period 1961–2010 in the Central European Plain showed a positive trend, ranging from 0.17 to 0.27 °C (10 years)$^{-1}$, and its fastest rise in spring reached from 0.08 to 0.43 °C (10 years)$^{-1}$. The increase in water temperature correlated strongly with rising air temperature (Marszelewski and Pius, 2016).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.4 Soil erosion and sediment load.

Summary from AR5

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (limited evidence, medium agreement, AR5-WGII Chapter 3)

New information since AR5

Climate change impacts on soil erosion have been observed over the world, and many studies suggest that the rainfall is the most direct influencing factor (Li and Fang, 2016). For example, in eight large Chinese rivers from 1991-2007, every 1% change in precipitation has led to a 2% change in sediment loads (Lu *et al*., 2013).

[Add more information based on long-term observed data in the FOD]

3.4.5.1.5 Extreme hydrological events (floods and droughts)

Summary from AR5

There is low confidence, due to limited evidence, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale. The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions (AR5 WGII Chapter 3).

New information since AR5

Since AR5, the number of studies based on long-term observed data has been limited yet. For example, Flood vulnerability is greatly affected by spatiotemporal changes in populations and assets and changed over time and space depending on local socioeconomic development conditions, including flood protection measures, topography and hydro-climatic conditions. Long-term analysis in flood vulnerability between 1960 and 2013 showed decreasing trends in global mortality rates and global loss rates, and inverse relationships were found between flood vulnerability and GDP per capita (Tanoue *et al.*, 2016).

3.4.5.2 Projected risks and potential adaptation (including limits)

3.4.5.2.1 Stream flow including availability of water resources and water use

[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Availability of water resources:

Summary from AR5

Climate change is projected to reduce renewable surface water resource significantly in most dry subtropical regions (robust evidence, high agreement). In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. (AR5-WGII Chapter 3)

New information since AR5:

Reduction of water resource availabilities under 2.0 ºC global mean temperature (GMT) rises is projected to be greater than 1.5 GMT rise, however socioeconomic condition might be greater than variation between GMT rises.

At the global scale, under GMT rises of around 1.5 ºC (transition GMT rise of RCP2.6 in 2011–2040) and around 2 ºC (transition of RCP2.6 in 2041–2070) compared to pre-industrial conditions, the projected ranges of changes in global irrigation water withdrawal are 0.9–1.8 and -0.0–2.0% respectively (one global hydrological model (GHM) by three GCMs) (Hanasaki *et al.*, 2013). Mean global warming levels of 1.5 ºC and 2 ºC (MAGICC6 with 19 GCMs using a pattern-scaling) are projected to expose an additional 4% and 8% of the world population to new or aggravated water scarcity, respectively, with >50% confidence (Gerten *et al.*, 2013). Under global warming of 1.7 °C and 2.7 °C above pre-industrial period (transition of RCP2.6 in 2041–2070), the multi-model medians with eleven GHMs by four GCMS project reduction in water resources, by at least one of the two criteria (experience a discharge reduction >20% and >1σ), about 8% and 14% of the global population, respectively (Schewe *et al.*, 2014). GMT rises of 1.5 ºC (transition of RCP2.6 in 2050, SSP1-5, 19 GCMs) would reduce exposure to increased ensemble mean of water scarcity by 184–270 million people compared to impacts under the 2 ºC (transition of RCP4.5 in 2050, SSP1-5, 19 GCMs), however variation between socioeconomic differences is greater than variation between GMT rises (Arnell and Lloyd-Hughes, 2014).

At the regional scale, In the United States, over the course of the 21st century and under one set of consistent socioeconomics, the reductions in water stress from slower rates of climate change resulting from emission mitigation are overwhelmed by the increased water stress from the emissions mitigation itself (Hejazi *et al.*, 2015).

Potential adaptation (including limit)

3.4.5.2.2 Water use

Summary from AR5

Significant reduction of renewable surface water and groundwater resources in most dry subtropical regions will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (limited evidence, medium to high agreement).

New information since AR5

Increase of water demand under 2.0 ºC GMT rises is projected to be similar to 1.5 ºC GMT rise.

Agriculture: Twenty five (five GHMs by five GCMs) ensemble projections under 1.5 ºC and 2 ºC (transition GMT rise of RCP2.6 and RCP4.5 in 2035–2065) compared to pre-industrial conditions show global irrigation water demand increases by ~8.6% and ~9.4%, respectively (Wada *et al.*, 2013).

[Energy Production, Municipal Services, Freshwater Ecosystems, etc. will be added in the FOD]

Potential adaptation (including limit)

3.4.5.2.3 Groundwater

[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Summary from AR5

Climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (robust evidence, high agreement). Climate change is likely to increase the frequency of short hydrological droughts (less surface water and groundwater) in presently dry regions (medium evidence, medium agreement). There is no evidence that groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (limited evidence, high agreement). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change. Carbon capture and storage can decrease groundwater quality.

New information since AR5
Climate change under 1.5 ºC GMT rise is projected to reduce groundwater resources significantly in some regions.

For a GMT rise of 1.5 ºC (transition of RCP 8.5) compared to pre-industrial conditions, an ensemble mean (five GCMS) of around 1.6% (range 1.0–2.2%) of global land area is projected to suffer from an extreme decrease of renewable groundwater resources of more than 70%, while the affected areas increase to 2.0% (range 1.1–2.6%) for a GMT rise of 2 ºC (transition of RCP8.5) (Portmann *et al.*, 2013). From 0.5–2 ºC rises of GMT, seasonal changes in discharge for the River Mitano under HadCM3 have a negligible influence on mean annual river discharge (<1% change from the discharge for the 1961–1990 baseline period) (Kingston and Taylor, 2010).

Potential Adaptation including limit

3.4.5.2.4 Water quality
[Add potential adaptation effect under 1.5 ºC GMT and 2.0 ºC GMT]

Summary from AR5
Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

New information since AR5
Reduction of water quality under 1.5 ºC and 2.0 ºC GMT rises is projected to be similar degree.
For example, the daily probability of exceeding the chloride standard for drinking water and the maximum duration of the exceedance in Lake IJsselmeer (Andijk) slightly increase to the same degree for GMT rises of 1.5 ºC and 2 ºC (Bonte and Zwolsman, 2010).

Potential Adaptation including limit

3.4.5.2.5 Soil erosion and sediment load
Summary from AR5
Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

New information since AR5
Published papers in respect of climate change impacts on soil erosion have been increasing since 2000 over the world (Li and Fang, 2016)

Potential Adaptation including limit

3.4.5.2.6 Extreme hydrological events (floods and droughts)
Summary from AR5
Floods. Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (limited evidence, medium agreement). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (high confidence). Global flood risk will increase in the future partly due to climate change (limited evidence, medium agreement).

Droughts. Climate change is likely to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of the 21st century under the RCP8.5 scenario (medium confidence). This is likely to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (medium evidence, medium agreement). Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand.

New information since AR5

Floods. GMT rises of 1.5 ºC would reduce exposure to increased flooding compared to impacts under the 2 ºC, however socioeconomic condition might be greater than variation between GMT rises.

GMT rises of 1.5 ºC (transition of RCP2.6 in 2050, SSP1-5, 19 GCMs) would reduce exposure to increased flooding by 23–34 million compared to impacts under the 2 ºC (transition of RCP4.5 in 2050, SSP1-5, 19 GCMs), however variation between socioeconomic differences is greater than variation between GMT rises (Arnell and Lloyd-Hughes, 2014). Impacts of global warming of 1.5 ºC and 2 ºC (transition, seven GCMs)are projected 100% and 170% increase in population affected and 120% and 170% increase in damage (Alfieri *et al.*, 2016). A significant increase in potential flood fatality (+5.7%) is projected without any adaptation if GMT increases by 1.5 °C to 2.0 °C, whereas an increase in potential economic loss (+0.9%) is not significant (Kinoshita *et al.*).

The difference of projected river discharge (three hydrological models and five GCMs) between global warming of 2 ºC (Transient, RCP4.5 during 2040–2059) and 1.5 ºC (Transient, RCP2.6 during 2020–2039) is positive for almost all the time scales (1.4%, 3.5%, 4.5%, 2.1%, 2.4% respectively for annual, spring, summer, 90% percentile and 10% percentile discharges) which suggests that the increment of 0.5 ºC could lead to more flood events in the in the Upper Yangtze River Basin (Chen *et al.*, 2017).

Droughts

Potential Adaptation including limit.

The differences in projected global economic damages with and without adaptation of flood protection show that adaptation measures have the potential to greatly reduce present and future flood damage, and the costs are often lower than the benefits (Winsemius *et al.*, 2016).

3.4.6 Food security and food production systems (including fisheries)

3.4.6.1 Observed impacts

For food security and food production systems quantifying the observed impacts of climate change is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine these.

3.4.6.1.1 Crop production

Impact studies on agricultural crops were focused on several components that contribute to food productions (crop suitability and yield, CO_2 fertilization, biotic and abiotic stresses).

The observed changes in climate parameters have already affected the crop suitability in many areas. These changes have produced effects on the main agricultural crops (e.g. wheat, rice, maize) determining shift of the cultivated areas or, however, changes on crop production. These impacts are evident in many areas of the world ranging from Asia (Sun et al., 2015; Chen et al., 2014; He and Zhou 2016) to Europe and are particularly important for typical local crops that are cultivated in specific climate conditions (e.g. Mediterranean crops like olive and grapevine) (Moriondo et al., 2013; Moriondo et al., 2013).

Several studies have estimated impacts of observed mean climate changes on crop yields over the past half century. Based on these studies, observed changes in climate seem to have negatively affected the production capacities of crops like wheat and maize (Lobell et al., 2011a); whilst the effects on rice and soybean yields have been smaller. Warming has produced positive effects on crop production in some high-latitude (Jaggard et al., 2007; Chen et al., 2010; Supit et al., 2010; Gregory and Marshall, 2012; Sun et al., 2015; Chen et al., 2014; He and Zhou 2016). In some instances, climate change has led to the possibility of more than one harvest per year (Sun et al., 2015; Chen et al., 2014).

Crop productions are strongly affected by increases in extreme events, but the quantification of these changes is more difficult. There is evidences that changes in the frequency of extreme events have affected cropping systems (e.g. changes in rainfall extremes, Rosenzweig et al., 2014; increases in hot nights, Welch et al., 2010, Okada et al., 2011; extremely high daytime temperature, Schlenker and Roberts, 2009, Jiao et al., 2016; drought, Jiao et al., 2016; chilling damage Jiao et al., 2016).

In addition to these, it is necessary to taken in to account the effects of changes in atmospheric composition (i.e. CO_2 and O_3 concentration). The increase of atmospheric CO_2 has played an important role in yields through by enhancing radiation and water use efficiencies. The rise in tropospheric O_3 has produced losses of yields of about 5-10% (van Dingenen et al. 2009).

Finally, the impacts on the occurrence, distribution and intensity of pest and disease on crop yields have been investigated. The results showed a general increase in pest and disease attacks related to higher winter temperatures that allowed pests to survive. Jiao et al., 2014 observed that climate warming and agricultural pests and diseases produced decrease in grain yield for winter wheat, maize and double cropping paddy rice in China.

3.4.6.1.2 Livestock production

The impacts of climate change on livestock production was considerably less studied than previous food systems. Attention was dedicated to ruminal diseases (e.g. blue-tongue virus (Guis et al., 2012) or zoonotic diseases. In both cases, climate change has facilitated the recent and rapid spread of the virus or ticks.

3.4.6.1.3 Fisheries Production

The detection and attribution of observed climate change impacts are different when inland and marine fisheries are considered.

Marine fishery is very sensitive to warming trends in water temperature. Several studies indicated that in Northern and Southern Oceans the observed increases in sea temperatures produced poleward migrations of marine species (Cheung et al., 2010, 2013; Last et al., 2011). These changes have particularly negative implications for coastal fisheries in tropical developing countries (Cheung et al., 2013). Moreover, specific attention was dedicated to fishery in coral reef ecosystems, where declines in coral reef cover, due to overfishing and rising ocean temperatures, led to declines in abundance of the majority of fish species associated with coral reefs (Wilson et al., 2006).

Less information is available on the impact of climate change fishery resources in freshwater systems and aquaculture. The studies conducted on these have not always produced consistent interpretations on the causes of the reduction of fish yields (e.g. increasing temperature, changes in fishery practices) (Ndebele-Murisa et al., 2011; Marshall 2012).

3.4.6.1.4 Food security

The impacts of observed climate change on food production are evident as reported in the above sections, but to quantify that these imply some effects on food security is rather difficult. Thus, there are few studies reporting clear links between climate change and food security. Among these Lobell et al., 2011a estimated that prices of traded food commodities increase due to the role of temperature and rainfall trends on food supply (+19%), that, however, was lower when increased CO_2 was considered (+6%).

3.4.6.2 Projected risks and potential adaptation (including limits)

3.4.6.2.1 Crop Production

Impact studies for major cereals showed that yields of maize and wheat begin to decline with 1 °C to 2 °C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3 °C to 5 °C. However, all crops showed negative yield impacts for 3 °C of warming without adaptation (Porter et al., 2014).

Relatively few studies considered impacts on cropping systems for scenarios where global mean temperatures increase within 1.5 °C. Schleussner et al. (2016) project that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and C&S America. Ricke et al. (2016) highlight how globally, cropland stability declines rapidly between 1 and 3ºC warming. Similarly, using the near term (2030-2040) as a proxy for 1.5 ºC warming, Niang et al. (2016) project significantly lower risks to crop productivity in Africa at this level than at 2 ºC warming.

3.4.6.2.2 Livestock Production

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases.

In temperate climate warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Simulations for grasslands (Graux et al., 2013) and sown pastures (Perring et al., 2010) also project negative impacts on forage quality.

High temperatures tended to reduce animal feeding and growth rates (André et al., 2011; Renaudeau et al., 2011). The impacts of a changing climate on dairy cow production showed that, in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century.

The possibility of supplying water for an increasing livestock population will be affected by climate change in many places. For example, Masike and Urich (2008) project that warming will cause an annual increase in cattle water demand.

Moreover, recent work indicated that heat stress can be responsible for the increase in mortality and economic losses (Vitali et al., 2009); it affects a wide range of parameters (e.g. embryonic development and reproductive efficiency in pigs, Barati et al., 2008; ovarian follicle development and ovulation in horses, Mortensen et al., 2009).

3.4.6.2.3 Fisheries Production

Expected changes in the intensity, frequency, and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification, and changes in precipitation with associated changes in groundwater and river flows are expected to determine significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (FAO, 2009a). At the global scale, projections suggested that climate change could lead to increase in fisheries yield in high-latitude regions, but a decrease in the tropics (Cheung et al., 2010).

3.4.6.2.4 Food security

The overall impact of climate change on food security is considerably more complex and greater than impacts on agricultural productivity. Several components of food security will be affected by climate change, ranging from food access, utilization and availability due to water, sanitation, and energy availability to food insecurity and price due to the frequency and severity of climate extremes.

Global temperature increases of about 4 °C or more, combined with increasing food demand, would pose large risks to food security globally and regionally, and risks to food security are generally greater in low latitude areas.

[INSERT BOX 3.1 HERE]

Box 3.1: Mediterranean Basin and the Middle East droughts

Over several millennia, human society and the natural environment have co-evolved in the Mediterranean Basin, laying the ground for very diverse and culturally rich communities. Even if the technology level may protect them in some way from climatic hazards, the consequences of climatic changes for inhabitants of the

Mediterranean continue to depend on the interplay of an array of societal and environmental factors (Holmgren et al. 2016). Previous IPCC assessments and recent publications have shown that the Mediterranean region (including both the northern and southern part of the Mediterranean basin) is projected to be particularly affected by regional changes in climate under increased warming, including consistent climate model projections of increased drying and strong regional warming (Seneviratne et al. 2012; Collins et al. 2013; Christensen et al. 2013; Greve and Seneviratne 2015; see also Section 3.3). These changes are also expected already at lower levels of warming (Section 3.3.4) and consistent with detected changes under the present level of warming (Greve et al. 2014, Section 3.3.4). Analyses show that risks of drying in the Mediterranean region can be substantially reduced if global warming is limited to 1.5 °C compared to 2 °C or higher levels of warming (Guiot and Cramer 2016b; see also Section 3.3.4).

Consistent with the highlighted projected regional climate changes in the Mediterranean region, the AR5 WGII Chapter 23 has shown that Southern Europe is particularly vulnerable to climate change (high confidence) as multiple sectors are projected to be adversely affected under higher levels of global warming (tourism, agriculture, forestry, infrastructure, energy, population health) (high confidence). The risk (with current adaptation) related to water decrease is high for a global warming of 2 °C and very high for a global warming of +4 °C (AR5 WGII Table 23.5). In regions affected by seasonal or chronic water scarcity, yield is strongly dependent on irrigation. In North African and Middle East countries (e.g., Algeria, Morocco, Syria, Tunisia, and Yemen), the total volume of water required for yield gap closure would exceed sustainable levels of freshwater consumption (i.e., 40% of total renewable surface and groundwater resources) (Davis et al., 2016)

This may be illustrated by example of the long-term history of the region of Northern Mesopotamia, which was recently subjected to an intense and prolonged drought episode between 2007 and 2010, partly related to La Nina events (Barlow et al. 2016). Very low precipitation generated a steep decline in agricultural productivity in the Euphrates and Tigris drainage basins, and displaced hundreds of thousands of people, mainly in Syria. Dried soils and diminished vegetation cover in the Fertile Crescent, as evident through remotely sensed enhanced vegetation indices, supported greater dust generation and transport to the Arabian Peninsula in 2007–2013 (Notaro et al. 2015). Effects have also been noticed on the water resource (Yazdanpanah et al. 2016) and the crop performance in Iran (Saeidi et al. 2017).

The Syrian up-rising, which began in March 2011 is the outcome of complex but interrelated factors (Gleick and Heberger, 2014; Kelley et al. 2015). While the main target of the multi-sided armed conflict has been a political regime change, the uprising was also triggered by a set of social, economic, religious and political factors leading to a disintegration of the country with a growing rural-urban divide, rising unemployment, and growing poverty (De Châtel 2014). The climate hypothesis has been fiercely contested and although causality cannot to be found in such a simple direct relationship, it cannot be denied that drought played a significant role in triggering the crisis, as this drought was the longest and the most intense in the last 900 years (Cook et al., 2015).

The Syrian example is but one in a long series of collapses or declines of civilizations in the Middle East which coincided with severe droughts, for example the end of the Bronze Age some 3200 years ago (Kaniewski et al. 2015). The spiral of decline into which the flourishing Eastern Mediterranean civilizations were plunged 3200 years ago, and the ensuing chaos, remains a persistent riddle in Near Eastern history. Most of the coastal cities of Eastern Mediterranean were destroyed, burned, and often left unoccupied thereafter, putting an end to the elaborate network of international trade that had ensured prosperity in the Aegean and the eastern Mediterranean. The rural settlements that emerged mainly persisted through adapted agro-pastoral activities and limited long-distance trade (Kaniewski et al., 2014). Drought may have hastened the fall of the Old World by sparking famine, invasions and conflicts, leading to the political, economic and cultural chaos referred to as the "Late Bronze Age crisis".

The 21st century drought and the Holocene droughts are climatically different. Trigo et al. (2010) have shown that the two-fold precipitation deficit in 1998-2002 and in 2007-2009 period lead to two long period with a 10m-decrease on the water level of Lake Tharthar, the largest lake in Iraq located between the Tigris and Euphrate. Impact on wheat and barley production was maximum in Iraq and Syria. Kelley et al. (2015)

showed that the precipitation deficit was strongly amplified by the high evapotranspiration due to high temperatures, while the Holocene droughts were only due to lack of precipitation during a long period (several centuries). This lead to the conclusion that future precipitation deficits amplified by high temperature are of high risk for the Mediterranean natural and managed ecosystems.

Box 1, Figure 1: Time series of precipitation in Middle East 3000 BP and 20-21st century

[END BOX 3.1 HERE]

3.5 Observed impacts and projected risks in human systems

3.5.1 Introduction

The human systems assessed in the Working Group II contribution to the IPCC AR5 were urban areas; rural areas; key economic sectors and services; human health; human security; and livelihoods and poverty. Human systems are embedded within the reasons for concern / key vulnerabilities assessed within the context of Article 2 of the UNFCCC (Cramer et al. 2014) and included.

- Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise;
- Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions;
- Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services;
- Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas;
- Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings;
- Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions;
- Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic; and
- Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.

The literature assessed in the AR5 typically focused on describing and quantifying linkages between weather and climate patterns and outcomes, with limited detection and attribution studies (Cramer et al. 2014). The observed changes in human systems described in this section should be taken within the context of section 3.4 because the risks of climate change to human systems are increased by the loss of ecosystem services (e.g. access to safe water) that are supported by biodiversity (Cramer et al. 2014). For all human systems, climate is one of many drivers of adverse outcomes, with patterns of demographic change, socioeconomic development, trade and tourism, and other factors also important. In addition, incomplete understanding of interactions among adverse outcomes across sectors and regions, and insufficient data, limits exploration of the full range of observed changes in human systems that could be attributed to climate change.

3.5.2 Urban areas --transport, energy, water, housing (including slums/informal settlements)

3.5.2.1 Observed impacts

Cramer et al. (2014) did not assess what climate-related impacts in urban areas could be attributed to climate change. Urbanization, development patterns, geography, and other factors can generate systemic risks that exceed the capacities of cities to prepare for and manage the risks of climate variability and change in, for example, low-lying coastal zones (Revi et al. 2014; Birkman et al. 2014; Rosenzweig et al. 2015; Morton et al. 2014). Extreme weather and climate events, such as inland and coastal flooding and drought, temperature extremes, reductions in air quality affect populations living in urban areas by increasing the risks of injuries, illnesses, and deaths, and by disrupting livelihoods and incomes. These can be compounded by geo-hydrological hazards, such as landslides and saltwater intrusion. Weather and climate variability also can affect water quality and quantity; functioning of critical infrastructure; and urban ecosystems, biodiversity, and ecosystem services. The coupled systems within cities can lead to novel, interacting hazards. The effects of weather and climate variability on rural and peri-urban agriculture, ecosystem services, and other sources of resources (e.g. firewood) affect cities through urban-rural interactions.

3.5.2.2 Projected risks at 1.5 °C and 2 ºC

Many large urban agglomerations in almost all continents will be exposed to a temperature rise of greater than 1.5 °C by mid-century under RCP2.6 (see Section 3.3).

[START BOX 3.2 HERE]

Box 3.2: Urban Climate

The climate in cities differs from surrounding regions due to the structures present and intensive human activity that occurs there. This is often referred to as the urban heat island (UHI) effect. Generally, cities are warmer than nearby rural areas, though this warming depends on many factors including the density of buildings, the geographical setting of the city, time of day, and season. In general, it has been found that the UHI effect is larger when there is: low wind speed; low cloud cover; large population or city size; in summer; and at night (Arnfield 2003).

Multiple mechanisms have been cited for causing the UHI (Rizwan et al. 2008; Zhao et al. 2014). Urban areas have relatively high levels of impermeable surfaces, leading to high runoff and hence lower evaporation due to lower moisture availability. This moves the surface temperature balance towards more sensible heat and higher temperatures. Common building materials such as concrete can store more energy than typical soils, causing a large diurnal shift in the surface energy balance. The release of this stored energy at night is a major cause of the night-time UHI. The arrangement of urban structures into street canyons typically reduces the effective albedo causing more energy to be absorbed. Street canyons also reduce the amount of open sky that can be seen from a point on the ground, and hence reduces the efficiency with which long-wave radiation can exit the urban environment. The effectiveness with which convection can mix temperatures from the surface into the lower atmosphere depends on the relative roughness of the city compared to nearby rural land. Human and industrial activities themselves emit heat that is directly added to the urban environment, this is called anthropogenic heat.

Studies have been conducted to estimate the UHI intensity in many cities. These studies have used a wide variety of methodologies (Mirzaei and Haghighat 2010), from observations (in-situ and remote sensing) to modelling across a wide range of scales. Using satellite data to examine the annual average surface UHI intensity in the 32 largest cities in China, Zhou et al. (2014) found large variability with values ranging from 0.01 to 1.87 °C in daytime. In the USA, Imhoff et al. (2010) found an average annual surface UHI intensity across the 38 largest cities of 2.9 °C, except for cities in arid and semi-arid climates where the cities were found to be cooler than their surrounding rural areas. Peng et al. (2012) used similar satellite data to examine the surface UHI across 419 global big cities. They estimate an annual average UHI intensity of 1.3 °C, with some cities reaching as high as 7 °C during daytime in summer, and a few cities surrounded by desert having negative surface UHI intensity. Tropical cities generally have UHI intensities that are lower than comparable temperate cities (Roth 2007). It should be noted that while the annual mean urban heat island intensity is a few degrees, the urban environment can enhance heat waves by more than the average UHI intensity (Li and Bou-Zeid 2013).

The urban environment can also affect the production of precipitation in and near the city (Han et al. 2014). Observational studies show that precipitating systems can be disrupted by cities while passing over them, and this can either increase or decrease precipitation depending on a complex interaction of factors including

UHI, city surface roughness, higher aerosol concentrations, local geography and water vapour supply. In some locations, such as tropical cities, this precipitation affect can be the dominant urban influence on the local climate (Argüeso et al. 2016).

Few studies into the combined effect of UHI and global warming have been conducted. McCarthy et al. (2010) run a global climate model at 300 km resolution, they found that UHI intensity could increase by as much as 30% but on average decreased by 6% for a doubling of CO_2. These simulations do not account for many of the differences between cities and demonstrate substantial errors in many locations. A small number of studies have used km scale regional climate models to investigate this for selected cities (Conlon et al. 2016; Grossman-Clarke et al. 2017; Kusaka et al. 2016; Georgescu et al. 2012; Argüeso et al. 2014). In general, these studies find that the UHI remains in a future warmer climate with increases in UHI intensity occurring due to increases in population and city size. The impact on humans depends on humidity as well as temperature changes. The first studies to look explicitly at these effects (Argüeso et al. 2015; Suzuki-Parker et al. 2015) suggest the possibility that future global warming and urban expansion could lead to more extremes in heat stress conditions.

[END BOX 3.2 HERE]

3.5.3 Rural areas

3.5.3.1 Observed impacts

Climate and non-climate stressors, including under-investment in agriculture, challenges with policies on land and natural resource use, and environmental degradation affect rural populations (Arent et al. 2014). Rural economies and livelihoods rely on a wide range of factors to support development, with climate change at the latter stages of complex interactions. Water supply, food security, and agricultural income will be the primary climate-mediated impacts through which climate change will operate. Cases of observed impacts on rural areas often suffer from problems of attribution, but evidence for observed impacts, is increasing. Impacts are expected to be substantial for low- and middle-income countries based on their dependence on agriculture and natural resources, low capacity to prepare for and manage change, and vulnerable geographic locations.

3.5.3.2 Projected risks at 1.5 °C and 2 °C

[To be completed for the FOD]

3.5.4 Key economic sectors and services

3.5.4.1 Introduction of context and expectations

Analyses of the key vulnerabilities (and opportunities) across economic sectors and services have, at least implicitly, appropriately cast their approaches in terms of risk – the product of likelihood and consequence. Limiting increases of global mean temperature from pre-industrial norms to 1.5 ºC instead of 2.0 ºC (or an additional 0.9 ºC instead of 1.4 ºC from the current 2017 benchmark) would change the likelihood of the intensities of potential impacts (as well as reduce the likelihood of experiencing amplified damages (or diminished net benefits) associated with even higher temperature stabilization limits. Chapter 10 of the WGII-AR5 correctly noted, at the top of its Executive Summary (page 662), that consequences will depend on a litany of confounding factors: "population, age, (the distribution of) income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development" that will "have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change {10.10}". These confounding factors are site-specific and development path dependent, and they affect the degree to which observed and projected ranges of impacts can be attributed to anthropogenic warming (the point of Chapter 10 of the WGII-AR5). It follows that the discussion in this section is similarly focused in time and space. It is therefore far from comprehensive in the sense of supporting aggregate portraits of overall economic risk even at a regional level; the literature will simply fall short in coverage to produce a credible version of the big picture.

The NAS report on Climate Stabilization Targets (Solomon, et al, 2010) adds even more complication by differentiating between transient and equilibrium warming. First of all, the observed economic impacts that frame the baseline for any consideration of projected futures depend on transient temperatures (that are roughly 50% of committed equilibrium temperatures). They are therefore simply snapshots of conditions that are characterized both by point estimates of temperature and associated other climate changes and their rates of change. Secondly since changes in global mean temperature depending on atmospheric concentrations at any point in time and because concentrations depend on cumulative emissions, only uncertain but instructive insights can be drawn between cumulative emissions (a viable indicator as the future unfolds) and the likelihoods of limiting temperature increases (at least with respect to the long run equilibrium). Combining Table 5.1 (page 23) and Figure Syn.1 (page 5) from the Solomon panel report (*XXXX*), it is possible, for example, to link equilibrium temperature targets of 1.0 ºC (plus or minus 0.3 ºC), 2.2 ºC (plus or minus 0.8 ºC) and 3.1 ºC (plus or minus 1.1 ºC) to cumulative emission limits of roughly 5600 (plus or minus 3000), 11000 (plus or minus 4000), and 17000 (plus or minus 7000) gigatonnes of carbon emissions, respectively (and anchored by the current total of about 5500 gigatonnes).

This brief discussion does not necessarily describe what the literature has done, but working through a risk-based organizational reading of past and more current literature informed by the confounding factors and the sources of fundamental scientific uncertainties provides insight into the criteria with which confidence in reported results can be assessed on analytical grounds – rigorous threads between global mean temperature and climate impacts that influence risks through the relative likelihoods of calibrated consequences, similarly rigorous process understanding of confounding factors, and (hopefully) how and when adaptation options might be undertaken to ameliorate either likelihoods or consequences. Doing so consistently offers the promise identifying the many knowledge gaps that still exist. Independent care should also be taken to note explicitly the geographic coverage of credible analyses and the inherent recognition of general equilibrium style interdependencies that will increasingly characterize the working of the global economy in autonomously spreading risk.

3.5.4.2 Identifying key sectors for possible coverage

Chapters 10 and 19 of WGII AR5 have identified key economic and services sectors and canvased literature that was available through 2013:

1. *Energy demand* (heating and cooling, at least, influenced directly by temperature change, but confounding factors can influence demand for transportation, agriculture, manufacturing, etc.)
2. *Energy supply* (depending on resources (water, wind, sunlight, technology, location), extreme weather events, etc.).
3. *Energy distribution infrastructure and economic organization* (the power grid, pipelines, river and ocean transport, etc.).
4. *Water supply infrastructure and water demand* (flooding, scarcity, competition for supply, etc.
5. *Transportation infrastructure* (flooding, intense heat or cold, extreme weather events (like intense precipitation, cyclones, etc.).
6. *Insurance and financial systems* (changes in the intensity and frequency of extreme weather events and associated consequences – droughts and wildfires, riverine and coastal flooding, extreme heat waves and severe cold spells, extreme precipitation and/or wind events, cyclones, etc.).
7. *Health Sector* (see Section 3.5.2.4)
8. *Agriculture* (temperature and precipitation, changes in the intensity and frequency of extreme weather events and associated consequences – droughts, flooding , extreme heat waves and severe cold spells, extreme precipitation and/or wind events, cyclones, etc.).
9. *Manufacturing and associated supply chains and distribution networks* (again, extreme weather events, sea level rise etc.).
10. *Retailing and associated supply chains* (business interruptions on the demand side and supply interruptions on the other, etc.).
11. *Coastal communities and commerce* (sea level rise, coastal storms of all magnitude, extreme weather

events, etc.).
12. *Recreation and Tourism* (extreme weather events, persistent changes in climate, etc.).

[START Box 3.3 HERE]

Box 3.3: Key economic sectors and services **-** An illustrative box example for coastal communities

Yohe et al. (2011) built on earlier work to consider economic damages distributions along the shoreline of Quincy, MA (a community in urban Boston, MA). They drew from quantitative estimates of the links between global mean temperature, sea level rise, and the return time of coastal storms of all severities to produce distributions of damages associated estimated from the pattern of coastal storms over a 30 year historical record. Damages were tied to breaching designated contours within Quincy and to property values. The impacts of rising seas (along two projected scenarios: 0.6 m and 1.0 m through 2100) were calibrated by tracing correlated changes in the mean of the historical distribution of damages under the assumption that the second moment of the distribution was fixed. The confounding factor of growing property values was captured by statistically estimated correlations with population and income and tracing projections of both into the future.

Box 3 Table 1 displays some results for the two sea level rise scenarios. The difference between the two panels could be a reflection of working to limit global mean temperature to 1.5 oC instead of 2.0 oC or 3.0 oC – if only starting along a lower emissions path reduced the likelihood of the 1.0m scenario relative to the 0.6m alternative.

[INSERT Box 3, Table 1 HERE]

Box 3, Table 1: Projected Annual Property Damage from Coastal Flooding for Selected Years through the Current Century. Source: Yohe, et al., 2010.

Panel A: Annual Damages Along a Sea Level Rise Scenario that Reaches 1.0m by 2100 (in millions of 2010 dollars)			
Year	**10th Percentile**	**Median**	**90th Percentile**
Current	$0	$0	$110
2030	$0	$50	$220
2050	$50	$110	$250
2070	$160	$230	$350
2090	$220	$290	$400
Panel B: Annual Damages Along a Sea Level Rise Scenario that Reaches 0.6m by 2100 (in millions of 2010 dollars)			
Year	**10th Percentile**	**Median**	**90th Percentile**
Current	$0	$0	$0
2030	$0	$0	$50
2050	$0	$40	$200
2070	$30	$110	$260
2090	$90	$150	$300

One $50 million adaptation project (a protecting barrier) was considered. Along the 1.0 m sea level rise scenario, the project would reduce expected damages by roughly $8 m per year from the date of installation; along the 0.6 m, by $2 per year. Two alternative decision rules were also considered. The first assumed that city planners applied a straight discounted expected benefit minus cost calculation. The second assumed that the planners recognized some aversion to risk so that economic value had to be calculated in terms of the discounted stream of certainty equivalents. For the 1.0 m scenario and a modest aversion to risk suggested that the internal rate of return for the adaptation project would exceed a interest rate threshold of 3% in 4 years' time (i.e., start now to build it) and a 5% threshold in 9 years' time. Along the 0.6 m scenario, those thresholds would be crossed in 25 years and 35 years, respectively. Knowing that global temperatures were heading toward the 1.5 °C limit would therefore buy city planners a considerable amount of time. If these planners were operating with an expected benefit-cost perspective, they would wait 9 years and 30 years with a 3% discount rate along the high and low scenarios, respectively; and they would wait 20 and 40 years with a 5% discount rate. Aversion to risk biases decisions toward the present and increases the value of information about the feasibility of low global mean temperature limits.

[END BOX 3.3 HERE]

[START BOX3.4 HERE]

Box 3.4: Key economic sectors and services - An illustrative box example for agriculture

Gourdji et al. (2013), report that the yields of major food source crops are relatively stable at current levels up to crop specific thresholds of maximum local temperatures during brief critical flowering stages early in the cycle of plant growth and crop maturity. For wheat, maize, rice, and soy, these thresholds are 34-35 °C, 35-36 °C, 36-37 °C, and 39-40 °C, respectively. A few days of exposure to temperatures above those threshold during flowering can kill the plants' flowers and thereby cause catastrophic reductions in yield. Box 4 Figure 1 shows the ranges of the percent of total harvested area that experience these the coincidence of exceeding the thresholds and the flowing period for these four major crops. The left portions of each panel reflect recent observations and explain (at least in part) the current relative stability in yields. The right portions display projected ranges in these percentages based on mean CMIP5 model projections for five decadal intervals from 2010 through 2050 along the SRES A1B scenario. Box 4 Figure 1 offers comparable evidence of geographic coverage across the globe. Since change in global mean temperature along A1B is projected to be between 0.8 °C and 1.2 °C in the 2020's and between 1.5 °C and 2.0 °C in the 2040's, comparisons of the 2020's and the 2040's is suggestive of the value (calibrated in crop specific yields whose values depend on location) of holding global mean temperatures below 1.5 °C rather than 2 °C; and comparisons up to the 2050's is suggestive of the value of reducing the likelihood of allowing warming up to 3.0 °C or beyond. It should be noted, though, in judging confidence in these conclusions, that the climate system would produce its own confounding factor – precipitation (and not just extreme weather events like severe downpours or prolonged drought). Plentiful and regular supplies of water and associated stable levels of ground moisture are not sufficient to eliminate the severity of these temperature thresholds.

[INSERT Box 3.4, Figure 1 HERE]

Box 3.4, Figure 1: Percent of total harvested area with at least 1, 5, or 10 reproductive days above the threshold over the recent past, as well as five decadal increments through 2050. Source: Figure 4 in Gourdji, et al. (2013).

[INSERT Box 3.4, Figure 2 HERE]

Box 3.4, Figure 2: Geographically differentiated projections for the 2030's (left column) and 2050's (right column) in reproductive days over the critical temperature thresholds during flowering for all four crops along from the CMIP5 models for scenario A1B. Source: Figure 3 in Gourdji,et al. (2013)

The economic implications of these results are also obscured by a myriad of socio-economic confounding factors, because they depend on the demand side of the markets for agricultural product which, in an integrated world economy, depends on global, regional, and national distributions of income and population as well as the willingness people around the world to substitute one source of necessary caloric intact for another. These are among the major factors that will frame the context for international trade over time, work with changing supply schedules to generate the uncertain evolution of relative prices of agricultural products, and thus distributions of the profitability of farming, itself, from one location to another). In addition, location-specific and development-path dependent adaptation options are available on the micro-scale supply side depending on available information about evolving local climate variability and longer-term projections of climate change, itself. The former can support responsive adaptation (like changing planting dates from one year to the next); the later can inform more expensive anticipatory adaption investments like crop switching. Both are more likely in developed nations, assuming that governmental research and monitoring programs for critical locally specific indicators of change produce robust and timely advice; government insurance and relief programs might also be expected in these countries. This essential support may not, however, be forthcoming even in relatively wealthy nations if their governments deliberately dismiss climate change as a source of risk. In developing countries, the capacity to adapt could be limited by scarcity in all of the above.

[END BOX 3.4 HERE]

3.5.4.3 Concluding remarks

Literature with which to fill this section will likely be very sparse because the complications of geography and confounding factors are enormous. Moreover, the authors of Chapter 10 of WGII AR5 are probably still correct in their assessment that these confounding factors will be more important in driving the economics of these key sectors than climate change for relatively small changes in global mean temperature (like 1.5 ºC or even 2.0 ºC). Moreover, most studies that do focus on climate change have not generally progressed beyond calibration the baselines drawn from recent observations of impacts calibrated in scientific metrics and not currency. Some studies might add projections of the economic impacts of specific but arbitrary climate change benchmarks that have no anchor in time and thus no way of placement along climate *cum* socio-economic scenarios. As evidence by the illustrations, few studies will provide detailed analysis of adaptation and global coverage.

3.5.5 Human health

3.5.5.1 Observed impacts

Climate change is adversely affecting human health by increasing exposure and vulnerability to climate-related stresses (Cramer et al. 2014). Observed and detected changes in climate change that affect human health included:

- Extreme weather events: climate-change-related risks from extreme events, such as heatwaves, extreme precipitation, and coastal flooding, are already moderate (high confidence) and high with 1 °C additional warming (medium confidence). Risks associated with some types of extreme events (e.g. extreme heat) increase further at higher temperatures (high confidence).
- Distribution of impacts: risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (medium to high confidence). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2 °C (medium confidence).

Further, climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses. For example, the interaction of climate change with food security can exacerbate malnutrition, increasing vulnerability of individuals to a range of diseases (high confidence).

While noting there are multiple social, environmental, and behavioural factors that influence heat-related mortality, Cramer et al. (2014) concluded that climate change has contributed to increased heat-related mortality in recent decades in Australia, England, and Wales, with medium confidence. Further, there is increasing evidence that high ambient carbon dioxide (CO_2) concentrations will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops. Cramer et al. (2014) concluded that changes in the latitudinal and altitudinal distribution of disease-carrying ticks in North America is consistent with observed warming trends but evidence was lacking of associated changes in the distribution of Lyme disease.

3.5.5.2 Detected impacts since AR5

There is strong evidence that changing weather patterns associated with climate change are shifting the geographic range, seasonality, and intensity of transmission of selected climate-sensitive infectious diseases (e.g. Semenza and Menne 2009), and increasing morbidity and mortality associated with extreme weather and climate events (e.g. Smith et al. 2014). Health detection and attribution studies conducted since the AR5 include heatwaves; Lyme disease in Canada; and *Vibrio* emergence in northern Europe provided evidence using multi-step attribution that climate change is adversely affecting human health (Ebi at al. 2017; Mitchell 2016; Mitchell et al. 2016). Changes in rates and geographic distribution of adverse health outcomes were detected, and, in each instance, a proportion of the observed changes could be attributed to changes in weather patterns associated with climate change.

Heatwaves: There is robust evidence that (1) climate change is affecting the frequency, intensity, and duration of heatwaves (IPCC 2013); and (2) exposure to high ambient temperatures is associated with excess morbidity and mortality (e.g. Gasparrini et al. 2015). Two studies undertook event attribution in Egypt and Europe. The risk of heat-related mortality increased about 70% in Central Paris and about 20% in London during the European heatwave of 2003 because of anthropogenic climate change, based on a comprehensive description of the heatwave, thousands of climate simulations of a high-resolution regional climate change generating a comprehensive description of the heatwave, and a health impact assessment using a percent increase in mortality per 1 °C increase in maximum apparent temperature (includes temperature and humidity) above city-specific thresholds (Mitchell et al. 2016). Anthropogenic climate change increased the likelihood of the 2015 Egyptian heatwave by 69% (± 17%), which increased heat stress (Mitchell 2016). The principal driver of human discomfort was high temperature, but relatively high humidity levels also played a role.

Taking another approach, mortality in Stockholm, Sweden in recent decades from heat extremes (days with temperatures above the 98th percentile of the 1900-1929 distribution) was double what would have occurred without climate change, adjusting for urbanization and the urban heat island effect, based on comparing mortality due to temperature extremes during the period 1980-2009 with expected mortality with 1900-1929 temperatures (Astrom et al. 2013).

Lyme disease in Canada: Climate could impact Lyme disease, a tick-transmitted zoonotic disease caused by the bacterium *Borrelia burgdorferi*, by affecting tick vector distributions and abundance; *B. burgdorferi* transmission cycle occurrence and efficiency (and thus the proportion of ticks infected); and the likelihood of transmission to humans. Lyme disease emerged in North America in the 1970s, with emergence associated with landscape change driven by socioeconomic factors that allowed abundance of a key animal host of the tick vector of Lyme disease (white-tailed deer) to rebound (Barbour and Fish 1993). Until the early 2000's there was only one known *I. scapularis* population in Canada. In the early 2000s, studies undertaken to explore what factors may limit the northward geographic spread of the tick (and Lyme disease risk) into Canada revealed that the habitat appeared suitable (Ogden et al. 2006a), with ticks being regularly dispersed into Canada (Ogden et al. 2006c), but that temperature conditions were likely too cold for the ticks in most of Canada (Ogden et al. 2005). A population model of *I. scapularis* incorporating known impacts of temperature on the tick was used to predict the geographic occurrence of current climatic suitability (Ogden et al. 2006b). Field studies in 2007 to validate the model predictions detected that incursion of the tick had begun (Ogden et al. 2008b). Since then, studies confirmed that tick vector populations and Lyme disease risk in Canada have emerged in a spatial pattern strongly associated with climate. Consistent positive associations have been found between the presence and abundance of *I. scapularis* ticks on animal hosts (rodents and deer) and temperature, accounting for a range of alternative potential drivers for tick occurrence (Bouchard et al. 2013a; Bouchard et al. 2013b; Gabriele-Rivet et al. 2015; Ogden et al. 2008b; Ogden et al. 2010). Passive tick surveillance data identified strong associations between the spatial occurrence of tick populations and the speed with which tick populations become established with temperature at a sub-national scale (Leighton et al. 2012; Koffi et al. 2012). Temperature increase was considered a key driver of emergence, with this temperature change attributed to climate change (Vincent et al. 2012) while other possible drivers of emergence were ruled out over most of the affected area (Ogden et al. 2014a). Over recent years the spread of the tick vector has been associated with steadily increasing numbers of Lyme disease cases, confirming that the ecological phenomenon of climate change-driven spread of the tick, accompanied by *B. burgdorferi* transmission cycles, with public health consequences in Canada (Ogden et al. 2014b; Ogden et al. 2015).

Vibrio emergence in the Baltic Sea: *Vibrio* bacteria are typically found in marine environments and can cause foodborne outbreaks and wound infections (Semenza et al. 2012a). Brackish saltwater and elevated sea surface temperature (SST) are ideal environmental growth conditions for certain *Vibrio* species (Semenza et al. 2012b). Between 1977-2010, 272 *Vibrio* cases, primarily *V. vulnificus* and *V. cholerae* (non O1/O139) wound infections, were identified in the Baltic Sea region (Baker-Austin et al. 2013) with the vast majority reported from 1997 onwards (234 cases, 85%). Significant and sustained warm water anomalies corresponded with increases in reported *Vibrio*-associated illness; for every increase in the maximum annual sea surface temperature (SST), the number of observed cases increased 1.93 times (Baker-Austin et al. 2013). In July and August 2014, the SST in the northern part of the Baltic exceeded historic records; exceeding the long-term average in some places by approximately 10 °C. *Vibrio* infections during the summer and autumn of 2014 in Sweden and Finland exceeded the number previously recorded (Baker-Austin et al. 2016).

3.5.5.3 Projected risks at 1.5 ºC and 2 ºC

Smith et al. (2014) concluded that if climate change continues as projected, major changes in ill health would include:

- Greater risks of injuries, diseases, and death due to more intense heatwaves and fires (very high confidence);
- Increased risk of undernutrition resulting from diminished food production in poor regions (high confidence);
- Consequences for health of lost work capacity and reduced labor productivity (high confidence);
- Increased risks of food- and waterborne diseases (very high confidence) and vectorborne diseases (medium confidence);
- Modest reductions in cold-related morbidity and mortality in some areas due to fewer cold extremes (low confidence), geographic shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds (medium confidence). These positive effects will be increasingly outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (high confidence).

Table 3.2 summarizes the projected risks to human health from studies assessed in the AR5 (Smith et al. 2014).

[INSERT TABLE 3.2 HERE]

Table 3.2: Projected risks to human health: studies cited in Smith et al. (2014)

Region	*Health outcome metric*	*Baselines*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
Global and 21 regions	Heat-related mortality in adults over 65 years of age	1961-1990	BCM2.0; EGMAM 1; EGMAM 2; EGMAM 3; CM4vl	A1B	2030; 2050				Population growth and aging; improved health in elderly due to economic development; three levels of adaptation (none, partial, and full)	Hales et al. 2014
Global	Heatwave area calculated as the area with heatwave	1971-2000	HadGEM 2-ES, bias corrected, from ISIMIP	RCP2.6 with SSP1; RCP6.0 with SSP2;	2030-2050; 2080-2100				Population density, % of population over 65 years of	Dong et al. 2015

	s divided by the total land area; number of heatwave days			RCP8.5 with SSP3					age; per capita GDP; education levels	
Global	Extremely hot summers over land areas (>3 SD anomalies)	1861-1880	26 models from CMIP5	RCP2.6; RCP4.5; RCP8.5	to 2100s	Temperature anomalies relative to 1951-1980		If the global mean temperature increases 2°C relative to the pre-industrial level, “extremely hot” summers are projected to occur over nearly 40% of the land area		Wang et al. 2015
Australia (five largest cities) and UK	Temperature-related mortality	1993-2006	UKCP09 from HadCM3; OzClim 2011	A1B, B1, A1FI	2020s; 2050s; 2080s				Projected population change	Vardoulakis et al. 2014
Australia	Temperature-related morbidity and mortality; days per year above 35°C	1971-2000	CSIRO	2030 A1B low and high; 2070 A1FI low and high	2030; 2070	4-6 dangerously hot days per year for un-acclimatized individuals	Sydney: from 3.5 days at baseline to 4.1-5.1 days; Melbourne: from 9 days at baseline to 11-13 days			Hanna et al. 2011
Brisbane, Sydney, and Melbourne Australia	Temperature-related mortality	1988-2009	62 GCMs, with spatial downscaling and bias correction	A2, A1B, B1	2050s; 2090s					Guo et al. 2016
Brisbane Australia	Years of life lost due to	1996-2003		Added 1 to 4C to observed	2000; 2050			Years of life lost increase		Huang et al. 2012

	temperature extremes (hot and cold)			daily temperature to project for 2050				by 1,104 (840-1,178) and cold days decrease by 1,112 (-1,337 to -871)		
Quebec, Canada	Heat-related mortality	1981-1999	Ouranos Consortium; SDSM downscaled HADCM3	A2 and B2 (projected impacts the same)	2020 (2010 – 2039); 2050 (2040 – 2069); 2080 (2070 – 2099)		*2% increase in 2020*	*4-6% increase in 2050*		Doyon et al. 2008
Montreal, Canada	Heat-related mortality	June – August 1990 - 2007	Canadian Global Circulation Model, 3.1; CSIRO Mark 3.5; ECHAM5; MRRC (Canadian regional climate model)	B1, A1B, A2	June-August 2020-2037				Assumed no change in mean daily death count; no demographic change; no change in ozone levels; no adaptation	Benmarhnia et al. 2014
USA	Heat-related mortality	1999-2003	GISS-II downscaled using MM5	A1B	2048-2052				Projected population change	Voorhees et al. 2011
USA	Avoided climate impacts of heatwaves and cold spells	1981-2005	CESM-LE with RCP8.5; CEMS-ME with RCP4.5. Includes urban heat island effect	RCP4.5; RCP8.5	2061-2080	Mean annual total heatwave days range from 4.4-6.3; similar range for cold spells				Oleson et al. 2015
USA, 209 cities	Heat- and cold-related mortality	1990 (1976-2005)	Bias corrected (BCCA) GFDL-CM3; MIROC5	RCP6.0	2030 (2016-2045); 2050 (2036-2065); 2100 (2086-2100)		Projected a net increase in premature deaths, with decreases in		Held population constant at 2010 levels; mortality associated with high temperatu	Schwartz et al. 2015

							temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city		res decreased between 1973-1977 and 2003-2006	
USA, 209 cities	Mortality associated with cold spells	1960-2050	CMIP5; 20 biased corrected (BCCAv2) multi-model dataset	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1960-2050				Assumed no change in demography or baseline mortality rate	Wang et al. 2016
USA, 82 communities	High-mortality heatwaves that increase mortality by 20%	1981-2005	CESM-LE with RCP85; CESM-ME with RCP4.5	RCP4.5; RCP8.5	2061-2080	Depending on modeling approach, 5-6 high mortality heatwaves annually, with approximately 2 million person-days of exposure per year			Projected population change (SSP3, SSP5) and three scenarios of adaptation (no, lagged, on pace:	Anderson et al. 2016
Washington State, USA	Heat-related mortality	1970-1999	PCM1; HadCM	Average of PCM1-B1 and HadCM-A1B; humidex baseline; number & duration of heatwaves calculated	2025; 2045; 2085		*Under moderate warming in 2045, 156 excess deaths in Seattle area*	*Under moderate warming in 2085, 280 excess deaths in Seattle area*	*Holding population constant at 2025 projections*	Jackson et al. 2010
Eastern	Heat-	2002-	CESM1.0	RCP8.5	2057-				Projected	Wu et

USA	related mortality	2004	downscaled using WRF		2059				population change in 2050	al. 2014
Rhode Island, USA	Heat-related emergency department admissions and heat-related morality	2005-2012	CMIP5 multi-model ensemble bias corrected (BCCA)	RCP 4.5; RCP 8.5	2046-2053; 2092-2099	Between 2005 and 2012, an increase in maximum daily temperature from 75 to 85F was associated with 1.3% and 23.9% higher rates of all cause and heat-related emergency department visits. Between 1999-2011, there was a 4.0% increase in heat-related mortality.				Kingsley et al. 2016
Boston, New York, Philadelphia, USA	Heat-related mortality	1971-2000	CMIP5 bias corrected (BCSD)	RCP 4.5; RCP 8.5	2010 – 2039; 2040 – 2069; 2070 - 2099				Population constant at 2000	Petkova et al. 2013
New York City, NY	Heat-related mortality	Each model's 30-year baseline average	Downscaled and bias corrected (BCSD) WCRP CMIP5, including 33 GCMs	RCP 4.5; RCP 8.5	2020s (2010-2039); 2050s (2040-2069); 2080s (2070-2099)	Decadal models from 1900 to 2006; heat-related mortality was relatively constant during			Five scenarios of population projections by gender; two adaptation scenarios plus no adaptation scenario	Petkova et al. 2017

						the first part of the 20th century, then decreased from the 1970s to 2000s				
Houston, Texas	Heat-related non-accidental mortality	1991-2010	CESM simulations for RCP8.5 and for RCP4.5; used HRLDAS for downscaling	RCP45; RCP8.5	2061-2080				Demographics and income in SSP3 and SSP5; urban heat island	Marsha et al. 2016
Europe	Heat-related respiratory hospital admissions	1981-2000	RCA3 dynamically downscaled results from CCCSM3, ECHAM5, HadCM3, ECHAM4	A1B; A2	2021-2050	The estimated proportion of respiratory hospital admissions due to heat was 0.18% at baseline in the EU27; the rate was higher for Southern Europe (0.23%)			Population projections	Astrom et al. 2013
UK	Temperature-related mortality	1993-2006	9 regional model variants of HadRm3-PPE-UK, dynamically downscaled	A1B	2000-2009; 2020-2029; 2050-2059; 2080-2089				Population projections to 2081	Hajat et al. 2014
Netherlands	Temperature-related	1981-2010	KNMI'14; G-scenario		2050 (2035-2065)	At baseline, the	Without adaptation,	Without adaptation, under the	Three adaptation scenarios,	Huynen and Marten

	mortality		is a global temperature increase of 1°C and W-scenario an increase of 2°C			attributable fraction for heat was 1.15% and for cold was 8.9%; or 1511 deaths from heat and 11,727 deaths from cold	under the G scenario, the attributable fraction for heat is 1.7-1.9% (3329-3752 deaths) and for cold is 7.5-7.9% (15,020-15,733 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	W scenario, the attributable fraction for heat is 2.2-2.5% (4380-5061 deaths) and for cold is 6.6-6.8% (13,149-13699 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	assuming a shift in the optimum temperature, changes in temperature sensitivity, or both; population growth and declining mortality risk per age group	s 2015
Skopje, Macedonia	Heat-related mortality	1986-2005; May - September	MRI-CGCM3; IPSL-CM5A-MR; GISS-E2-R	RCP8.5	2026-2045; 2081-2100				Two models to project population growth; PM10	Martinez et al. 2016
Japan, Korea, Taiwan, USA, Spain, France, Italy	Heat-related mortality for 65+ age group	1961-1990	BCM2	A1B	2030; 2050				Three adaptation assumptions: 0, 50, and 100%	Honda et al. 2014
Beijing, China	Heat-related mortality	1970-1999	Downscaled and bias corrected (BCSD) 31 GCMs in WCRP CMIP5; monthly change factors were applied to daily	RCP4.5; RCP8.5	2020s (2010-2039), 2050s (2040-2069), 2080s (2070-2099)	Approximately 730 additional annual heat-related deaths in 1980s			Adults 65+ years of age; no change plus low, medium, and high variants of population growth; future adaptation based on Petkova et	Li et al. 2016

			weather data to create a projection						al. 2014, plus shifted mortality 5%, 15%, 30%, 50%	
Beijing, China	Cardiovascular and respiratory heat-related mortality	1971-2000	Access 1.0; CSIRO Mk3.6.0; GFDL-CM3; GISS E2R; INM-CM4	RCP4.5; RCP8.5	2020s; 2050s; 2080s	Baseline cardiovascular mortality 0.396 per 100,000; baseline respiratory mortality 0.085 per 100,000				Li et al. 2015
Africa	Five thresholds for number of hot days per year when health could be affected, as measured by maximum apparent temperature	1961-2000	CCAM (CSIRO) forced by coupled GCMs: CSIRO; GFDL20; GFDL 21; MIROC; MPI; UKMO. CCAM was then downscaled. Biased corrected using CRU TS3.1 dataset	A2	2011-2040; 2041-2070; 2071-2100				Projected population in 2020 and 2025	Garland et al. 2015

3.5.6 Human security

3.5.6.1 Observed impacts

Cramer et al. (2014) assessed the literature on the connection between climate change and human security, focusing on conflict and involuntary migration. Each is multi-causal, with multiple drivers and embedded social processes. Overall, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and on traditional ecological knowledge.

For the collapse of civilizations and large-scale climate disruptions, such as severe or prolonged drought, Cramer et al. (2014) concluded the detection of a climate change effect and an assessment of the importance of its role could only be made with low confidence because of the limits of understanding and data. Research on the relationship between interannual climate variability (not climate change) and civil conflict at that time generally focused on Africa. Although statistical relationships were identified in some studies, the results were challenged in others on technical and substantive grounds. Therefore, Cramer et al. (2014) concluded neither the detection of an effect of climate change on civil conflict nor an assessment of the magnitude of any such effect could be made with a degree of confidence.

The potential impacts of climate change on human displacement and migration was identified in the AR5 as an emerging risk (Oppenheimer et al. 2014). The social, economic, and environmental factors underlying migration are complex and varied; therefore, it was not possible to detect the effect of observed climate change or assess its possible magnitude with any degree of confidence (Cramer et al. 2014).

3.5.6.2 Projected risks at 1.5 °C and 2 ºC

3.5.7 Livelihood and poverty

3.5.7.1 Observed impacts

Olsson et al. (2014) concluded that climate-related hazards can interact with and exacerbate other factors that affect livelihoods, particularly people living in poverty. Poor people are poor for different reasons, so are not uniformly affected and not all vulnerable people are poor. The impacts of climate-related hazards are felt through losses in food, water, and household security, and through a loss of sense of place. Changes in weather patterns can alter rural livelihoods, with consequences for socioeconomic development, including poverty traps. The general high vulnerability of marginalized and disadvantaged groups means climate-related hazards can worsen poverty and inequalities, creating new vulnerabilities and opportunities.

3.5.7.2 Projected risks at 1.5 °C and 2 °C

Risks to livelihoods and poverty are expected to worsen with additional climate change because of the interactions of weather and change with non-climate stressors and entrenched structural inequities to shape vulnerabilities (Olsson et al. 2014). The extent to which climate change could slow economic growth and poverty reduction, further erode food security, and create new poverty traps would affect the number and distribution of poor individuals and communities between now and 2100. Most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia. Climate change is expected to exacerbate multi-dimensional poverty in most low- and middle-income countries, including high mountain states, countries at risk of sea level rise, and countries with indigenous populations.

3.5.8 Observed adaptation effectiveness and barriers

3.5.8.1 Investments in adaptation

Developed countries set a roadmap of climate finance reaching US$ 100 billion annually, with half earmarked for adaptation (Parker et al. 2014). Current projections suggest that even if doubled, adaptation funds will not reach the target (Carty et al. 2016). In 2014, assistance for adaptation was 6.9% of the $392 billion spent globally on climate action (CPI 2015, Olhoff et al. 2016). Of the $27 billion in adaptation funds spent globally in 2014, about 84% came from development finance institutions and 3% from the international climate change adaptation funds (CPI 2015, Olhoff et al. 2016). East Asia and the Pacific received 46%, followed by Sub-Saharan Africa, and Latin America and the Caribbean. Nearly 55% of adaptation money was invested in water and wastewater management and another 13% for agriculture and forestry management. Other major sectors included disaster management, infrastructure, energy and built environment, and coastal protection. Upper estimates of the global adaptation costs are $300 billion by 2030 and $500 billion by 2050 (Olhoff et al. 2016).

3.5.8.2 Effectiveness of adaptation investments

3.5.8.3 Evidence of barriers and limits to adaptation

3.5.8.4 Maladaptation

3.6 Avoided impacts and reduced risks at 1.5 °C compared with 2 °C

3.6.1 Introduction

A framework that aggregates projected risks as a function of global mean temperature change into five categories known as 'Reasons for Concern' was provided by Oppenheimer et al. (2014) (AR5, Chapter 19). Risks are classified as moderate, high, or very high (see AR5 Chapter 19 for details and findings). A recent paper reviewed the framework's conceptual basis and the risk judgments made in Oppenheimer et al. (2014), confirming most judgements made in the light of more recent literature (O'Neill, *XXXX*). The approach of Oppenheimer et al. (2014), with updates in terms of the risk aggregations as informed by the most recent literature, is therefore adopted for the analysis and narrative presented in Section 3.6.

The five reasons for concern, for which risks are aggregated, are:

1. Unique and threatened systems (text to be added to Section 3.6.2.2 using Section 3.4 when complete)
2. Extreme weather events (text to be added to Section 3.6.2.1 using Section 3.3)
3. Distribution of impacts (text to be added using Section 3.5)
4. Global aggregate impacts (text to be added once using Sections 3.1 to 3.5)
5. Large scale singular events (text to be completed using Section 3.3)

A graphical presentation of how the five reasons of concern accrue with global warming between 0 °C and 2 °C above pre-industrial levels is provided in Figure 3.11. Note that this follows the analysis of Oppenheimer et al. (2014), but with the risk assessments based on the most recent literature.

[INSERT FIGURE 3.11 HERE]

Figure 3.11: How reasons for concern accrue with global warming of between 0 and 2 °C above pre-industrial levels. The portion of the diagram that relates to warming of 1.5 °C versus 2 °C is magnified.

3.6.2 Synthesis on previous sections (3.3-3.5)

3.6.2.1 The physical climate system

[Assessment of avoided changes in climate extremes and the physical climate system in general, for 1.5 °C vs 2 °C of global warming, will be based on Section 3.3.]

3.6.2.1.1 Changes in climatological averages (Section 3.3 text to serve as input)
3.6.2.1.2 Changes in extreme weather events (Section 3.3 text to serve as input)
3.6.2.1.3 Large scale singular events (Section 3.3 text to serve as input)

3.6.2.2 Natural and managed ecosystems

[Unique and threatened systems (Section 3.4 text to be used as input)]

A number of studies quantify the risks avoided from constraining warming to various levels, for example 2 °C relative to 4 °C. A review in preparation (Arnell et al) concludes that 1.8 °C warming avoids 32-88% of the impacts accruing by 2100 (depending on sector) compared to a impacts for 4 °C of warming, whereas 2 °C warming avoids 24-82% of the risks accruing by 2100 (this is a multi-sectoral study covering human exposure to water stress, fluvial flooding, coastal flooding, and heatwaves; loss of crop suitability; and biodiversity loss – an important input to Section 3.6 to be reported on in more detail in a next version of the section). Moreover, (Warren et al. *in prep*, the study is called AVOID) is to provide an update to Arnell et al and quantifies the impacts avoided at 1.5 °C relative to the same 4 °C baseline, encompassing a slightly wider set of risk metrics.

Some impacted sectors display a non-linear relationship between the magnitude of the risks and °C of global warming, in which impacts increase rapidly during lower levels of warming and then rise more slowly or not at all as warming continues, most of the sector has already been impacted. The most prominent examples are coral reef bleaching, which increases very rapidly between 1 and 2 °C warming, at which point most of the impacts that could occur are realised; water scarcity, which increases rapidly between 0 and 2 °C warming, and more slowly as warming continues; and cropland stability, which decreases rapidly between 1 and 3 °C warming, decreasing slowly thereafter. This means that the benefits of constraining warming to 1.5 °C are projected to be large for coral reefs, water scarcity, and cropland stability (Ricke et al. 2016).

Similarly Schleussner et al. (2016) highlights coral reefs, water supplies, and tropical agriculture (including in West Africa, SE Asia, N&C America) as benefiting strongly from constraining warming to 1.5 °C compared to 2 °C. Also highlighted as benefiting strongly are Mediterranean regions (confirmed by a variety of other studies, see Section 3.4.1) and areas at risk of coastal flooding due to sea level rise (see Section 3.3.12)

3.6.2.3 Human systems

[Assessment of avoided impacts on human systems, for 1.5 °C vs. 2 °C, will be based on Section 3.5.]

3.6.2.4 Global aggregate impacts (will be composed using section 3.3 to 3.5 as key inputs)

3.6.3 Benefits analysis Economic benefit analysis for a 1.5 °C vs. 2 °C global temperature goals

Benefits of achieving the 1.5 °C temperature goal, as opposed to the 2 °C goal, have been outlined summarized in Section 3.6.2 in terms of avoided risks to the physical climate system, natural and managed ecosystems and human systems. This section reviews the available evidence and literature that estimates the economic benefits to be obtained through impacts that are avoided for the case of 1.5 °C warming vs. 2 °C warming. Potential trade-offs, in terms of higher mitigation costs to achieve the 1.5 °C temperature goals as opposed to the 2 °C goal, are also analysed.

3.6.3.1 Reduced climate costs under 1.5 °C vs. 2 °C of global warming.

3.6.3.2 Potential trade-offs: mitigation costs associated with achieving 1.5 °C vs. 2 °C of global warming.

3.6.4 Compare 1.5 °C vs. 2 °C and NDCs/other baselines; consider impacts of alternative interpretations of 1.5 scenarios

3.6.4.1 Benefits of achieving the 1.5 °C and 2 °C of global warming as opposed to lower mitigation futures.

3.6.4.1.1 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with the Paris Agreement NDCs

3.6.4.1.2 Summary of benefits of 1.5 °C or 2 °C of global warming compared to temperature increases associated with low mitigation: 3 °C and 4 °C of global warming

3.6.4.1.3 Interpretation of different definitions of the 1.5 °C temperature increase to benefits analysis

The definition of 1.5 °C of global warming, as defined in the Paris Agreement, refers to the stabilisation of global average surface temperature increase to 1.5 °C above the pre-industrial average. Reduced benefits associated with “overshoot” scenarios, where temperature initially exceeds the 1.5 °C threshold but then decreases until it stabilises at or below this threshold are to be analysed in this sub-subsection. Also to be discussed is the value of studying impacts associated with 1.5 °C of global warming from “transient” simulations, where the global temperature reaches thresholds of 1.5 °C or 2 °C of warming, and then continues to increase. To what extent do impacts calculated for say a 20-year period around the year when a 1.5 °C increase first occurs differ from impacts associated with a 1.5 °C stabilisation scenario? This question is important to answer from a pragmatic perspective, since numerous studies on climate change impacts under different global temperature goals based on the CMIP5 GCMs and CORDEX RCMs make use of exactly this latter definition.

3.6.5 Reducing hot spots of change for 1.5 ºC and 2 ºC global warming

This section will use the analysis of Section 3.3.14 (analysis of hots spots in the physical climate system under 1.5 °C and 2 °C of global warming) as its key input – towards describing the extent that climate change hot spots may be expected to be avoided, reduced or lessened in impact by restricting the global temperature increase to 1.5 °C or less. The subsection will discuss similarly the reductions of hots spots in natural systems and socio-economic human systems for 1.5 °C vs. 2 °C of global warming, building on the analysis of Sections 3.4 and 3.5.

3.6.5.1 The physical climate system

3.6.5.2 Natural and managed ecosystems

3.6.5.3 Socio-economic human systems

3.6.6 Tipping points

Tipping points refer to critical thresholds in a system, that when exceeded may lead to a significant change in the state of the system. Critical to the climate change mitigation effort is to understand the sensitivities of tipping points in the physical climate system, ecosystems and human systems. This subsection reviews tipping points across these three main areas of relevance, within the context of the different sensitivities to 1.5 °C vs. 2 °C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed.

3.6.6.1 Tipping points in the physical climate system

The cryosphere: West-Antarctic ice sheet, Greenland ice sheet, Arctic sea-ice.
Ocean circulation: Thermohaline circulation (Atlantic Meridional Overturning Current and the formation of Antarctic Bottom Water).
Monsoon systems: Indian Monsoon, West African Monsoon, East African Monsoon.
Global modes of variability: El Niño Southern Oscillation (ENSO)
Global carbon cycle: Role of the Southern Ocean as a carbon sink; permafrost
The discussion to be developed will follow to some extent that of Lenton et al. (2008).

3.6.6.2 Tipping points in ecosystems

Biomes: Rain forests (focus on Amazon), boreal forests, tundra.
Coral reefs under global temperature goals and ocean acidification (e.g. Hoegh-Goldberg et al., 2007).

3.6.6.3 Tipping points in human socio-economic systems

Heat-waves, unprecedented heat and human health
Agricultural systems (key staple crops and livestock production under different degrees of global warming)

[INSERT TABLE 3.3 HERE]

Table 3.3: Summary of enhanced risks in the exceedance of tipping points for 3 °C and 2 °C vs. 1.5 °C of global warming.

3.7 Implications for impacts, adaptation and vulnerability of different mitigation pathways reaching 1.5 °C including potential overshoot

This section will draw together the previous discussion about expected changes, impacts and implications into a number of trajectories or pathways, focusing on two groups: (1) those that increase to 1.5 °C without an overshoot and (2) those have an overshoot (and then a trend back down toward 1.5 °C). We will be developing this further when we are in Exeter - after having input and literature from the authorship team. Given the work still to be done, we have left this with minimal text with the idea that we will develop it as we head towards FOD and in the Exeter meeting.

Special attention will be given to when the overshooting is happening throughout the 20th century and if patterns in climate changes and extremes are different to those at 1.5 °C in 2100, in case literature is available.

Many climate models exhibit an overshoot of the final average global temperature. This has become highly likely in many scenarios that ultimately trend toward 1.5 °C above preindustrial period. The reasons for overshoot arise from momentum within the climate system, as well as socio-economic drivers and emission reduction pathways. In situations where pathways overshoot, average global temperatures increase to beyond 1.5 °C before 2100 but may come down several decades later. While the average global temperature of 1.5 °C may be achieved, the pathway may lead to unacceptable impacts and tipping points which mean that the cost of undergoing an overshoot may rule against it being a suitable pathway.

3.7.1 Pathways without overshoot

3.7.1.1 Likely pattern of extremes and other changes in climate system

This section will draw on work done in previous chapters with respect to pathways which trend upwards and stabilise at or below 1.5 °C. Particular attention will be paid to expected extremes as well as trends, and yet associated changes that are expected in the climate system. Drawing on previous chapters, this section will also describe the sorts of changes expected at local and global levels under a gradual rise to 1.5 °C and stabilisation.

3.7.1.2 Implications for natural and human systems

The ramifications for natural systems of a 1.5 °C increase in average global surface temperature are explored here, drawing on the observations and conclusions from previous parts of chapter 3. There would also be a discussion of the implications for humans, potentially highlighting positive and negative elements of achieving stabilisation without overshoot.

3.7.1.3 Adaptation options

This section would explore the adaptation options in the light of a climate that stabilizes at 1.5 °C. It is anticipated that this discussion will investigate and highlight the options for adaptation for a stabilization scenario, in preparation for the next section which looks at the challenges associated with overshoot.

3.7.2 Pathways with overshoot

3.7.2.1 Likely pattern of extremes and other changes in climate system

This section will explore the changes that are likely to occur in pathways which include an overshoot relative to the final stabilization point of 1.5 °C. In addition to temperature, this section will draw on previous discussions of the types of changes that occur at different levels (e.g. 2 °C or higher).

3.7.2.2 Implications for natural and human systems

Implications of these pathways will be explored - especially the consequences of pathways which go through different levels of overshoot. As with the previous section it will draw on our understanding of responses by biological and human systems, and will assess risks that arise.

3.7.2.3 Adaptation options

This section will investigate how risks associated with pathways which include an overshoot relative to the final stabilization point of 1.5 °C might be mitigated through adaptation strategies.

3.7.3 Non-greenhouse gas implications and projected risks of mitigation scenarios

3.7.3.1 Influence on weather and climate extremes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology that can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g. Mueller et al. 2015) or reforestation/revegetation endeavours (e.g. Feng et al. 2016; Sonntag et al. 2016) and changes in land management (e.g. Luyssaert et al. 2014; Hirsch et al. 2017) that can involve double cropping (e.g. Jeong et al. 2014; B. Mueller et al. 2015; Seifert & Lobell 2015), irrigation (e.g. Sacks et al. 2009; Lobell et al. 2009; Cook et al. 2011; Qian et al. 2013; de Vrese et al. 2016; Pryor et al. 2016; Thiery et al. 2017), tillage (e.g. Lobell et al. 2006; Davin et al. 2014) and wood harvest (e.g. Lawrence et al. 2012).

The magnitude of the biophysical impacts has been found to be potentially large for extreme temperatures. Indeed, both changes induced by modifications in moisture availability and irrigation, or by changes in surface albedo, tend to be larger for hot extremes than for mean temperatures (e.g. Seneviratne et al. 2013; Davin et al. 2014; Wilhelm et al. 2015; Hirsch et al. 2017; Thiery et al. 2017). For moisture availability, the reason is related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne 2012; Seneviratne et al. 2013b). In the case of surface albedo, cooling associated with higher albedo (e.g. in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al. 2014). The overall effect of either irrigation or albedo has been found to be at the most of the order of ca. 1-2 °C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Hirsch et al. 2017, see Figure 3.12).

3.7.3.2 Impacts on natural and human systems (e.g. competition for land/water and food/energy security)

In addition to the biophysical feedbacks on climate from land use change and land management, there are potential consequences for certain ecosystem services. This includes climate change induced changes in crop yield (e.g. (Schlenker and Roberts 2009; Butler and Huybers 2012; van der Velde et al. 2012; Asseng et al. 2013; Lobell et al. 2014; Asseng et al. 2015) which may be further exacerbated by competing demands for arable land between reforestation mitigation activities, growing crops for BECCS, increasing food production to support larger populations or urban expansion (e.g. see review by Smith et al. 2010). In particular, some land management practices may have further implications for food security where some regions may have increases or decreases in yield when ceasing tillage (Pittelkow et al. 2014). The reductions in yield driven by climate change and/or land management decisions are likely to have implications for food security with subsequent economic consequences (e.g. Nelson et al. 2014; Dalin & Rodríguez-Iturbe 2016; Muratori et al. 2016, 2014). In other cases, limitations on the potential of particular mitigation activities may be constrained by resource availability (e.g. Smith et al. 2015).

[INSERT FIGURE 3.12 HERE]

Figure 3.12: Regional temperature scaling with CO_2 concentration (ppm) over 1850 to 2099 for two different SREX regions: Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850-1870 and units are in ˚C. The black line in all panels denotes the 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation on (blue), and irrigation with albedo +0.10 (green). Adapted from Figure 3 of Hirsch et al. (2017).

3.7.4 Long-term implications

References

Ackerman, F., E. A. Stanton, and R. Bueno, 2010: Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE. *Ecol. Econ.*, **69**, 1657–1665, doi:10.1016/j.ecolecon.2010.03.013.
Aich, V., and Coauthors, 2016: Flood projections within the Niger River Basin under future land use and climate change. *Sci. Total Environ.*, **562**, 666–677, doi:10.1016/j.scitotenv.2016.04.021. http://www.ncbi.nlm.nih.gov/pubmed/27110979.
Alfieri, L., P. Burek, L. Feyen, and G. Forzieri, 2015: Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci*, **19**, 2247–2260, doi:10.5194/hess-19-2247-2015. www.hydrol-earth-syst-sci.net/19/2247/2015/.
Alfieri, L., B. Bisselink, F. Dottori, G. Naumann, A. de Roo, P. Salamon, K. Wyser, and L. Feyen, 2017: Global projections of river flood risk in a warmer world. *Earth's Futur.*, **5**, 171–182, doi:10.1002/2016EF000485. http://doi.wiley.com/10.1002/2016EF000485.
Alin, S., and Coauthors, 2014: Attribution of corrosive bottom-water conditions to ocean acidification and other estuarine drivers in Puget Sound: an updated analysis. *Salish Sea Ecosyst. Conf.*,. http://cedar.wwu.edu/ssec/2014ssec/Day2/45.
Alkama, R., L. Marchand, A. Ribes, and B. Decharme, 2013: Detection of global runoff changes: results from observations and CMIP5 experiments. *Hydrol. Earth Syst. Sci.*, **17**, 2967–2979, doi:10.5194/hess-17-2967-2013. http://www.hydrol-earth-syst-sci.net/17/2967/2013/.
Allen, M., 2003: Liability for climate change. *Nature*, **421**, 891–892, doi:10.1038/421891a. http://www.ncbi.nlm.nih.gov/pubmed/12606972.
Altieri, A. H., and K. B. Gedan, 2015: Climate change and dead zones. *Glob. Chang. Biol.*, **21**, 1395–1406, doi:10.1111/gcb.12754.
Anderegg, W. R. L., and Coauthors, 2015: Tropical nighttime warming as a dominant driver of variability in the terrestrial carbon sink. *Proc. Natl. Acad. Sci. U. S. A.*, **112**, 15591–15596, doi:10.1073/pnas.1521479112.
Andersen, L. E., and D. Verner, 2010: *Social impacts of climate change in Chile: A municipal level analysis of the effects of recent and future climate change on human development and inequality*. Washington, DC, 1-29 pp. http://documents.worldbank.org/curated/en/319821468266372780/Social-impacts-of-climate-change-in-Chile-a-municipal-level-analysis-of-the-effects-of-recent-and-future-climate-change-on-human-development-and-inequality.
Anderson-Teixeira, K. J., and Coauthors, 2015: CTFS-ForestGEO: A worldwide network monitoring forests in an era of global change. *Glob. Chang. Biol.*, **21**, 528–549, doi:10.1111/gcb.12712.
André, G., B. Engel, P. B. M. Berentsen, T. V. Vellinga, and A. G. J. M. Oude Lansink, 2011: Quantifying the effect of heat stress on daily milk yield and monitoring dynamic changes using an adaptive dynamic model. *J. Dairy Sci.*, **94**, 4502–4513, doi:10.3168/jds.2010-4139. http://www.sciencedirect.com/science/article/pii/S0022030211004619.
Andrews, O. D., N. L. Bindoff, P. R. Halloran, T. Ilyina, and C. Le Quéré, 2013: Detecting an external influence on recent changes in oceanic oxygen using an optimal fingerprinting method. *Biogeosciences*, **10**, 1799–1813, doi:10.5194/bg-10-1799-2013.
Arent, D. J., R. S. J. Tol, E. Faust, J. P. Hella, S. Kumar, K. M. Strzepek, F. L. Tóth, and D. Yan, 2014: Key economic sectors and services. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 659–708 https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap10%7B_%7DFINAL.pdf.
Argüeso, D., A. Di Luca, and J. P. Evans, 2016: Precipitation over urban areas in the western Maritime Continent using a convection-permitting model. *Clim. Dyn.*, **47**, 1143–1159, doi:10.1007/s00382-015-2893-6. http://link.springer.com/10.1007/s00382-015-2893-6.
Argüeso, D., J. P. Evans, L. Fita, and K. J. Bormann, 2014: Temperature response to future urbanization and climate change. *Clim. Dyn.*, **42**, 2183–2199, doi:10.1007/s00382-013-1789-6. http://link.springer.com/10.1007/s00382-013-1789-6.
Argüeso, D., J. P. Evans, A. J. Pitman, and A. Di Luca, 2015: Effects of city expansion on heat stress under climate change conditions. *PLoS One*, **10**, e0117066, doi:10.1371/journal.pone.0117066. http://www.ncbi.nlm.nih.gov/pubmed/25668390.
Armsworth, P. R., and Coauthors, 2015: Are conservation organizations configured for effective adaptation to global change? *Front. Ecol. Environ.*, **13**, 163–169, doi:10.1890/130352.
Arnell, N. W., and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Clim. Change*, **122**, 127–140, doi:10.1007/s10584-013-0948-4. http://link.springer.com/10.1007/s10584-013-0948-4.
Arnfield, A. J., 2003: Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.*, **23**, 1–26, doi:10.1002/joc.859. http://doi.wiley.com/10.1002/joc.859.

Asadieh, B., N. Krakauer, and B. Fekete, 2016: Historical Trends in Mean and Extreme Runoff and Streamflow Based on Observations and Climate Models. *Water*, **8**, 189, doi:10.3390/w8050189. http://www.mdpi.com/2073-4441/8/5/189.

Asseng, S., and Coauthors, 2015: Rising temperatures reduce global wheat production. *Nat. Clim. Chang.*, **5**, 143–147, doi:10.1038/nclimate2470. http://www.nature.com/doifinder/10.1038/nclimate2470.

Asseng, S., and Coauthors, 2013: Uncertainty in simulating wheat yields under climate change. *Nat. Clim. Chang.*, **3**, 827–832, doi:10.1038/nclimate1916. http://www.nature.com/doifinder/10.1038/nclimate1916.

Åström, D. O., A. Tornevi, K. L. Ebi, J. Rocklöv, and B. Forsberg, 2015: Evolution of Minimum Mortality Temperature in Stockholm, Sweden, 1901–2009. *Environ. Health Perspect.*, **124**, doi:10.1289/ehp.1509692. http://ehp.niehs.nih.gov/15-09692.

Aström, D., A. Tornevi, K. L. Ebi, J. Rocklöv, and B. Forsberg, 2016: Evolution of minimum mortality temperature in Stockholm, Sweden, 1901-2009. *Environ. Health Perspect.*, **124**, 740–744, doi:10.1289/ehp.1509692. http://ehp.niehs.nih.gov/15-09692.

Ayers, J. M., and S. Huq, 2009: The Value of Linking Mitigation and Adaptation: A Case Study of Bangladesh. *Environ. Manage.*, **43**, 753–764, doi:10.1007/s00267-008-9223-2. http://link.springer.com/10.1007/s00267-008-9223-2.

Báez, S., L. Jaramillo, F. Cuesta, and D. A. Donoso, 2016: Effects of climate change on Andean biodiversity: a synthesis of studies published until 2015. *Neotrop. Biodivers.*, **2**, 181–194, doi:10.1080/23766808.2016.1248710. https://www.tandfonline.com/doi/full/10.1080/23766808.2016.1248710.

Báez, S., and Coauthors, 2015: Large-scale patterns of turnover and basal area change in Andean forests. *PLoS One*, **10**, 1–14, doi:10.1371/journal.pone.0126594. http://dx.plos.org/10.1371/journal.pone.0126594.

Baker-Austin, C., J. A. Trinanes, S. Salmenlinna, M. Löfdahl, A. Siitonen, N. G. H. Taylor, and J. Martinez-Urtaza, 2016: Heat Wave–Associated Vibriosis, Sweden and Finland, 2014. *Emerg. Infect. Dis.*, **22**, 1216–1220, doi:10.3201/eid2207.151996. http://wwwnc.cdc.gov/eid/article/22/7/15-1996%7B_%7Darticle.htm.

Baker-Austin, C., J. A. Trinanes, N. G. H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza, 2012: Emerging Vibrio risk at high latitudes in response to ocean warming. *Nat. Clim. Chang.*, **3**, 73–77, doi:10.1038/nclimate1628. http://www.nature.com/doifinder/10.1038/nclimate1628.

Baker-Austin, C., J. A. Trinanes, N. G. H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza, 2013: Emerging Vibrio risk at high latitudes in response to ocean warming. *Nat. Clim. Chang.*, **3**, 73–77, doi:10.1038/nclimate1628. http://www.nature.com/doifinder/10.1038/nclimate1628.

Bakun, A., 1990: Global climate change and intensification of coastal ocean upwelling. *Science (80-.).*, **247**, 198–201, doi:10.1126/science.247.4939.198. http://www.ncbi.nlm.nih.gov/pubmed/17813287.

Ban, N., J. Schmidli, and C. Schär, 2014: Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. *J. Geophys. Res. Atmos.*, **119**, 7889–7907, doi:10.1002/2014JD021478. http://doi.wiley.com/10.1002/2014JD021478.

Barati, F., B. Agung, P. Wongsrikeao, M. Taniguchi, T. Nagai, and T. Otoi, 2008: Meiotic competence and DNA damage of porcine oocytes exposed to an elevated temperature. *Theriogenology*, **69**, 767–772, doi:10.1016/j.theriogenology.2007.08.038. http://www.sciencedirect.com/science/article/pii/S0093691X07007200.

Barbour, A., and D. Fish, 1993: The biological and social phenomenon of Lyme disease. *Science (80-.).*, **260**, 1610–1616, doi:10.1126/science.8503006. http://www.sciencemag.org/cgi/doi/10.1126/science.8503006.

Barlow, M., and Coauthors, 2016: A Review of Drought in the Middle East and Southwest Asia. *J. Clim.*, **29**, 8547–8574, doi:10.1175/JCLI-D-13-00692.1. http://journals.ametsoc.org/doi/10.1175/JCLI-D-13-00692.1.

Barnes, M. L., and Coauthors, 2016: Vegetation productivity responds to sub-annual climate conditions across semiarid biomes. *ECOSPHERE*, **7**, doi:10.1002/ecs2.1339.

Bartlein, P. J. J., and Coauthors, 2011: Pollen-based continental climate reconstructions at 6 and 21 ka: A global synthesis. *Clim. Dyn.*, **37**, 775–802, doi:10.1007/s00382-010-0904-1.

Bednaršek, N., T. Klinger, C. J. Harvey, S. Weisberg, R. M. McCabe, R. A. Feely, J. Newton, and N. Tolimieri, 2017: New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. *Ecol. Indic.*, **76**, 240–244, doi:10.1016/j.ecolind.2017.01.025. http://linkinghub.elsevier.com/retrieve/pii/S1470160X17300316.

Betts, R. A., N. Golding, P. Gonzalez, J. Gornall, R. Kahana, G. Kay, L. Mitchell, and A. Wiltshire, 2015: Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, **12**, 1317–1338, doi:10.5194/bg-12-1317-2015. http://www.biogeosciences.net/12/1317/2015/.

Biesbroek, G. R., R. J. Swart, and W. G. M. van der Knaap, 2009: The mitigation–adaptation dichotomy and the role of spatial planning. *Habitat Int.*, **33**, 230–237, doi:10.1016/j.habitatint.2008.10.001. http://linkinghub.elsevier.com/retrieve/pii/S019739750800060X.

Bindoff, N. L., and Coauthors, 2013: Detection and Attribution of Climate Change: from Global to Regional Supplementary Material. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to* *the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds. http://www.climatechange2013.org/.

Birkmann, J., R. Licker, M. Oppenheimer, M. Campos, R. Warren, G. Luber, B. C. O'Neill, and K. Takahashi, 2014: Cross-chapter box on a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in the WGII contribution to the fifth assessment report. *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 113–121.

Bonte, M., and J. J. G. Zwolsman, 2010: Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. *Water Res.*, **44**, 4411–4424, doi:10.1016/j.watres.2010.06.004. http://www.sciencedirect.com/science/article/pii/S0043135410003799.

Bouchard, C., and Coauthors, 2013: Harvested white-tailed deer as sentinel hosts for early establishing Ixodes scapularis populations and risk from vector-borne zoonoses in southeastern Canada. *J. Med. Entomol.*, **50**, 384–393. http://www.ncbi.nlm.nih.gov/pubmed/23540128.

Bouchard, C., G. Beauchamp, P. a Leighton, R. Lindsay, D. Bélanger, and N. H. Ogden, 2013: Does high biodiversity reduce the risk of Lyme disease invasion? *Parasites {&} vectors*, **6**, 195, doi:10.1186/1756-3305-6-195. http://aem.asm.org/cgi/doi/10.1128/AEM.02636-10.

Bring, A., and Coauthors, 2016: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *J. Geophys. Res. Biogeosciences*, **121**, 621–649, doi:10.1002/2015JG003131.

Buchner, B. K., C. Trabacchi, F. Mazza, D. Abramskiehn, and D. Wang, 2015: *Global Landscape of Climate Finance 2015*. 15 pp. https://climatepolicyinitiative.org/wp-content/uploads/2015/11/Global-Landscape-of-Climate-Finance-2015.pdf.

Burrows, M. T., and Coauthors, 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**, 492–495, doi:10.1038/nature12976. http://www.nature.com/doifinder/10.1038/nature12976.

Butler, E. E., and P. Huybers, 2012: Adaptation of US maize to temperature variations. *Nat. Clim. Chang.*, **3**, 68–72, doi:10.1038/nclimate1585. http://www.nature.com/doifinder/10.1038/nclimate1585.

Byass, P., 2009: Climate change and population health in Africa: where are the scientists? *Glob. Health Action*, **2**, 2065, doi:10.3402/gha.v2i0.2065. https://www.tandfonline.com/doi/full/10.3402/gha.v2i0.2065.

Camilloni, I. A., R. I. Saurral, and N. B. Montroull, 2013: Hydrological projections of fluvial floods in the Uruguay and Paran{á} basins under different climate change scenarios. *Int. J. River Basin Manag.*, **11**, 389–399, doi:10.1080/15715124.2013.819006. http://www.tandfonline.com/doi/abs/10.1080/15715124.2013.819006.

Campbell-Lendrum, D., D. D. Chadee, Y. Honda, L. Qiyong, J. M. Olwoch, B. Revich, and R. Sauerborn, 2014: *Human Health: Impacts, Adaptation, and Co-Benefits*. Cambridge University Press, 709-754 pp. https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap11%7B_%7DFINAL.pdf.

Canada. Health Canada., and Public Health Agency of Canada., *Canada communicable disease report : CCDR.* Health Canada, http://www.phac-aspc.gc.ca/publicat/ccdr-rmtc/15vol41/dr-rm41-06/ar-03-eng.php.

Cao, L., and K. Caldeira, 2008: Atmospheric CO2 stabilization and ocean acidification. *Geophys. Res. Lett.*, **35**, 1–5, doi:10.1029/2008GL035072.

Cao, L., K. Caldeira, and A. K. Jain, 2007: Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophys. Res. Lett.*, **34**, doi:10.1029/2006GL028605.

Carty, T., J. Kowalzig, and A. Peterson, 2015: Climate Finance Shadow Report 2016: Lifting the lid on progress towards the {$}100 billion commitment. https://www.oxfam.org/sites/www.oxfam.org/files/file%7B_%7Dattachments/bp-climate-finance-shadow-report-031116-en.pdf.

Chen, B., X. Zhang, J. Tao, J. Wu, J. Wang, P. Shi, Y. Zhang, and C. Yu, 2014: The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agric. For. Meteorol.*, **189**, 11–18, doi:10.1016/j.agrformet.2014.01.002.

Chen, C., E. Wang, Q. Yu, and Y. Zhang, 2010: Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. *Clim. Change*, **100**, 559–578, doi:10.1007/s10584-009-9690-3. http://link.springer.com/10.1007/s10584-009-9690-3.

CHEN, C., G. ZHOU, and L. ZHOU, 2014: Impacts of Climate Change on Rice Yield in China From 1961 to 2010 Based on Provincial Data. *J. Integr. Agric.*, **13**, 1555–1564, doi:10.1016/S2095-3119(14)60816-9. http://linkinghub.elsevier.com/retrieve/pii/S2095311914608169.

Chen, I.-C., J. K. Hill, R. Ohlemüller, D. B. Roy, and C. D. Thomas, 2011: Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science (80-.).*, **333**. http://science.sciencemag.org/content/333/6045/1024.

Chen, J., and Coauthors, 2017: Assessing changes of river discharge under global warming of 1.5 °C and 2 °C in the upper reaches of the Yangtze River Basin: Approach by using multiple- GCMs and hydrological models. *Quat. Int.*, doi:10.1016/j.quaint.2017.01.017. http://www.sciencedirect.com/science/article/pii/S1040618216312174.

Cheruy, F., J. L. Dufresne, F. Hourdin, and A. Ducharne, 2014: Role of clouds and land-atmosphere coupling in

midlatitude continental summer warm biases and climate change amplification in CMIP5 simulations. *Geophys. Res. Lett.*, **41**, 6493–6500, doi:10.1002/2014GL061145. http://doi.wiley.com/10.1002/2014GL061145.
CHEUNG, W. W. L., V. W. Y. LAM, J. L. SARMIENTO, K. KEARNEY, R. E. G. WATSON, D. ZELLER, and D. PAULY, 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Chang. Biol.*, **16**, 24–35, doi:10.1111/j.1365-2486.2009.01995.x. http://doi.wiley.com/10.1111/j.1365-2486.2009.01995.x.
Cheung, W. W. L., R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497**, 365–368, doi:10.1038/nature12156. http://www.ncbi.nlm.nih.gov/pubmed/23676754.
Christensen, J. H., and Coauthors, 2017: Regional Climate Projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.T. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt and H.L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter11.pdf.
Christensen, J. H., and Coauthors, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Christensen, J. H., and O. B. Christensen, 2003: Climate modelling: Severe summertime flooding in Europe. *Nature*, **421**, 805–806, doi:10.1038/421805a. http://www.ncbi.nlm.nih.gov/pubmed/12594501.
Church, J. A., and Coauthors, 2013: Sea Level Change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds., Cambridge University Press, United Kingdom and New York, NY, USA https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5%7B_%7DChapter13%7B_%7DFINAL.pdf.
Cloke, H. L., F. Wetterhall, Y. He, J. E. Freer, and F. Pappenberger, 2013: Modelling climate impact on floods with ensemble climate projections. *Q. J. R. Meteorol. Soc.*, **139**, 282–297, doi:10.1002/qj.1998. http://doi.wiley.com/10.1002/qj.1998.
Collins, M., and Coauthors, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA http://www.climatechange2013.org/images/report/WG1AR5%7B_%7DChapter12%7B_%7DFINAL.pdf.
Conlon, K., A. Monaghan, M. Hayden, O. Wilhelmi, M. Cline, and E. Wood, 2016: Potential Impacts of Future Warming and Land Use Changes on Intra-Urban Heat Exposure in Houston, Texas. *PLoS One*, **11**, e0148890, doi:10.1371/journal.pone.0148890. http://dx.plos.org/10.1371/journal.pone.0148890.
Cook, B. I., K. J. Anchukaitis, R. Touchan, D. M. Meko, and E. R. Cook, 2016: Spatiotemporal drought variability in the Mediterranean over the last 900 years. *J. Geophys. Res. Atmos.*, **121**, 2060–2074, doi:10.1002/2015JD023929. http://doi.wiley.com/10.1002/2015JD023929.
Cook, B. I., M. J. Puma, and N. Y. Krakauer, 2011: Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Clim. Dyn.*, **37**, 1587–1600, doi:10.1007/s00382-010-0932-x. https://pubs.giss.nasa.gov/docs/2011/2011%7B_%7DCook%7B_%7Dco07500u.pdf.
Cook, B. I., M. J. Puma, @bullet Nir, and Y. Krakauer, 2010: Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. doi:10.1007/s00382-010-0932-x. https://pubs.giss.nasa.gov/docs/2011/2011%7B_%7DCook%7B_%7Dco07500u.pdf.
Costello, A., and Coauthors, 2009: Managing the health effects of climate change. *Lancet*, **373**, 1693–1733, doi:10.1016/S0140-6736(09)60935-1. http://linkinghub.elsevier.com/retrieve/pii/S0140673609609351.
Cowtan, K., and R. G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.*, **140**, 1935–1944, doi:10.1002/qj.2297. http://doi.wiley.com/10.1002/qj.2297.
Crabbe, R. A., J. Dash, V. F. Rodriguez-Galiano, D. Janous, M. Pavelka, and M. V Marek, 2016: Extreme warm temperatures alter forest phenology and productivity in Europe. *Sci. Total Environ.*, **563**, 486–495, doi:10.1016/j.scitotenv.2016.04.124.
CRAINE, J. M., A. J. ELMORE, K. C. OLSON, and D. TOLLESON, 2010: Climate change and cattle nutritional stress. *Glob. Chang. Biol.*, **16**, 2901–2911, doi:10.1111/j.1365-2486.2009.02060.x. http://doi.wiley.com/10.1111/j.1365-2486.2009.02060.x.
Cramer, W., G. W. Yohe, M. Auffhammer, C. Huggel, U. Molau, A. da Silva Dias, M.A.F. Solow, D. A. Stone, and L. Tibig, 2014: Detection and attribution of observed impacts. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 979–1037 http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/WGII/WGIIAR5-Chap18%7B_%7DFINAL.pdf.

da Silva, R. M., C. A. G. Santos, M. Moreira, J. Corte-Real, V. C. L. Silva, and I. C. Medeiros, 2015: Rainfall and river flow trends using Mann–Kendall and Sen's slope estimator statistical tests in the Cobres River basin. *Nat. Hazards*, **77**, 1205–1221, doi:10.1007/s11069-015-1644-7. http://link.springer.com/10.1007/s11069-015-1644-7.

Dai, A., 2016: Historical and Future Changes in Streamflow and Continental Runoff. John Wiley {&} Sons, Inc., 17–37 http://doi.wiley.com/10.1002/9781118971772.ch2.

Dalin, C., and I. Rodríguez-Iturbe, 2016: Environmental impacts of food trade via resource use and greenhouse gas emissions. *Environ. Res. Lett.*, **11**, 35012, doi:10.1088/1748-9326/11/3/035012. http://stacks.iop.org/1748-9326/11/i=3/a=035012?key=crossref.aca35fdbf8a6626deefa7bd98d76a627.

Dankers, R., and Coauthors, 2014: First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3257–3261, doi:10.1073/pnas.1302078110. http://www.ncbi.nlm.nih.gov/pubmed/24344290.

Davin, E. L., S. I. Seneviratne, P. Ciais, A. Olioso, and T. Wang, 2014: Preferential cooling of hot extremes from cropland albedo management. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 9757–9761, doi:10.1073/pnas.1317323111. http://www.ncbi.nlm.nih.gov/pubmed/24958872.

Davis, K. F., M. C. Rulli, F. Garrassino, D. Chiarelli, A. Seveso, and P. D'Odorico, 2017: Water limits to closing yield gaps. *Adv. Water Resour.*, **99**, 67–75, doi:10.1016/j.advwatres.2016.11.015. http://dx.doi.org/10.1016/j.advwatres.2016.11.015.

De Châtel, F., 2014: The Role of Drought and Climate Change in the Syrian Uprising: Untangling the Triggers of the Revolution. *Middle East. Stud.*, **50**, 521–535, doi:10.1080/00263206.2013.850076. http://www.tandfonline.com/doi/abs/10.1080/00263206.2013.850076.

de Vrese, P., S. Hagemann, and M. Claussen, 2016: Asian irrigation, African rain: Remote impacts of irrigation. *Geophys. Res. Lett.*, **43**, 3737–3745, doi:10.1002/2016GL068146. http://doi.wiley.com/10.1002/2016GL068146.

Delcloo, A. W., R. De Troch, O. Giot, R. Hamdi, A. Deckmyn, and P. Termonia, 2016: Future Climate and Air Quality of the Brussels Capital Region for the 2050s Under A1B Scenario. *Air Pollution Modeling and its Application XXIV*, D.G. Steyn and N. Chaumerliac, Eds., Springer International Publishing, Cham, 201–205 http://dx.doi.org/10.1007/978-3-319-24478-5%7B_%7D33.

Déqué, M., S. Calmanti, O. B. Christensen, A. Dell Aquila, C. F. Maule, A. Haensler, G. Nikulin, and C. Teichmann, 2016: A multi-model climate response over tropical Africa at +2°C. *Clim. Serv.*, doi:10.1016/j.cliser.2016.06.002. http://www.sciencedirect.com/science/article/pii/S240588071630005X.

Deser, C., R. Knutti, S. Solomon, and A. S. Phillips, 2012: Communication of the role of natural variability in future North American climate. *Nat. Clim. Chang.*, **2**, 775–779, doi:10.1038/nclimate1562. http://www.nature.com/doifinder/10.1038/nclimate1562.

Dietz, S., 2011: High impact, low probability? An empirical analysis of risk in the economics of climate change. *Clim. Change*, **108**, 519–541, doi:10.1007/s10584-010-9993-4.

Diffenbaugh, N. S., and F. Giorgi, 2012: Climate change hotspots in the CMIP5 global climate model ensemble. *Clim. Change*, **114**, 813–822, doi:10.1007/s10584-012-0570-x. http://www.ncbi.nlm.nih.gov/pubmed/24014154.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas, 2009: Ocean Acidification: The Other CO 2Problem. *Ann. Rev. Mar. Sci.*, **1**, 169–192, doi:10.1146/annurev.marine.010908.163834. http://www.annualreviews.org/doi/abs/10.1146/annurev.marine.010908.163834%7B%25%7D5Cnpapers2://publication/doi/10.1146/annurev.marine.010908.163834.

Dugarsuren, N., and C. Lin, 2016: Temporal variations in phenological events of forests, grasslands and desert steppe ecosystems in Mongolia: a remote sensing approach. *Ann. For. Res.*, **59**, 175–190, doi:10.15287/afr.2016.400.

Durack, P. J., S. E. Wijffels, and R. J. Matear, 2012: Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000. *Science (80-.).*, **336**, 455–458, doi:10.1126/science.1212222. http://www.sciencemag.org/cgi/doi/10.1126/science.1212222.

Ebi, K. L., N. H. Ogden, J. C. Semenza, and A. Woodward, Detecting and attributing health burdens to climate change. *Revis.*, **in revisio**, in revision.

Ellis, E. C., J. O. Kaplan, D. Q. Fuller, S. Vavrus, K. K. Goldewijk, and P. H. Verburg, 2013: Used planet: A global history. *Proc. Natl. Acad. Sci. U. S. A.*, **110**, 7978–7985, doi:10.1073/pnas.1217241110.

Elsner, J. B., J. P. Kossin, and T. H. Jagger, 2008: The increasing intensity of the strongest tropical cyclones. *Nature*, **455**, 92–95, doi:10.1038/nature07234. http://www.nature.com/doifinder/10.1038/nature07234.

Emanuel, K., R. Sundararajan, and J. Williams, 2008: Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. *Bull. Am. Meteorol. Soc.*, **89**, 347–367, doi:10.1175/BAMS-89-3-347. http://journals.ametsoc.org/doi/abs/10.1175/BAMS-89-3-347.

Engelbrecht, F. A., J. L. McGregor, and C. J. Engelbrecht, 2009: Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *Int. J. Climatol.*, **29**, 1013–1033, doi:10.1002/joc.1742. http://doi.wiley.com/10.1002/joc.1742.

Erfanian, A., G. Wang, M. Yu, and R. Anyah, 2016: Multimodel ensemble simulations of present and future climates over West Africa: Impacts of vegetation dynamics. *J. Adv. Model. Earth Syst.*, **8**, 1411–1431, doi:10.1002/2016MS000660. http://doi.wiley.com/10.1002/2016MS000660.

et al Greve, No Title. *submitted*,.

et al O'Neill, No Title. *in prep.*,.

FAO, 2009: Introduction. *Climate change implications for fisheries and aquaculture*, K. Cochrane, C. De Young, D. Soto, and T. Bahri, Eds., Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 1–5 http://www.fao.org/docrep/012/i0994e/i0994e00.htm.

Feely, R. A., and Coauthors, 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuar. Coast. Shelf Sci.*, **183**, 260–270, doi:10.1016/j.ecss.2016.08.043.

Feng, X., and Coauthors, 2016: Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nat. Clim. Chang.*, **6**, 1019–1022, doi:10.1038/nclimate3092. http://www.nature.com/doifinder/10.1038/nclimate3092.

Fernandez, P., S. Mourato, and M. Moreira, 2016: Social vulnerability assessment of flood risk using GIS-based multicriteria decision analysis. A case study of Vila Nova de Gaia (Portugal). *Geomatics, Nat. Hazards Risk*, **7**, 1367–1389, doi:10.1080/19475705.2015.1052021. http://www.tandfonline.com/doi/full/10.1080/19475705.2015.1052021.

Fernandez, P., S. Mourato, M. Moreira, and L. Pereira, 2016: A new approach for computing a flood vulnerability index using cluster analysis. *Phys. Chem. Earth, Parts A/B/C*, **94**, 47–55, doi:10.1016/j.pce.2016.04.003. http://linkinghub.elsevier.com/retrieve/pii/S147470651630016X.

Fischer, E. M., and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Chang.*, **5**, 560–564, doi:10.1038/nclimate2617. http://www.nature.com/doifinder/10.1038/nclimate2617.

Fischer, E. M., J. Sedláček, E. Hawkins, and R. Knutti, 2014: Models agree on forced response pattern of precipitation and temperature extremes. *Geophys. Res. Lett.*, **41**, 8554–8562, doi:10.1002/2014GL062018. http://doi.wiley.com/10.1002/2014GL062018.

Fisher, J. B., and Coauthors, 2013: African tropical rainforest net carbon dioxide fluxes in the twentieth century. *Philos. Trans. R. Soc. B-BIOLOGICAL Sci.*, **368**, doi:10.1098/rstb.2012.0376.

Frost, A. J., and Coauthors, 2011: A comparison of multi-site daily rainfall downscaling techniques under Australian conditions. *J. Hydrol.*, **408**, 1–18, doi:10.1016/j.jhydrol.2011.06.021. http://www.sciencedirect.com/science/article/pii/S0022169411004525.

Gabriele-Rivet, V., and Coauthors, 2015: Different Ecological Niches for Ticks of Public Health Significance in Canada. *PLoS One*, **10**, e0131282, doi:10.1371/journal.pone.0131282. http://dx.plos.org/10.1371/journal.pone.0131282.

García Molinos, J., and Coauthors, 2015: Climate velocity and the future global redistribution of marine biodiversity. *Nat. Clim. Chang.*, **6**, 83–88, doi:10.1038/nclimate2769. http://www.nature.com/doifinder/10.1038/nclimate2769.

Gasparrini, A., and Coauthors, 2015: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*, **386**, 369–375, doi:10.1016/S0140-6736(14)62114-0. http://linkinghub.elsevier.com/retrieve/pii/S0140673614621140.

Gattuso, J.-P., and Coauthors, 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science (80-.).*, **349**, aac4722--1--aac4722--10, doi:10.1126/science.aac4722. http://www.sciencemag.org/cgi/doi/10.1126/science.aac4722.

Georgescu, M., M. Moustaoui, A. Mahalov, and J. Dudhia, 2012: Summer-time climate impacts of projected megapolitan expansion in Arizona. *Nat. Clim. Chang.*, **3**, 37–41, doi:10.1038/nclimate1656. http://www.nature.com/doifinder/10.1038/nclimate1656.

Gerten, D., and Coauthors, 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environ. Res. Lett.*, **8**, 34032, doi:10.1088/1748-9326/8/3/034032. http://stacks.iop.org/1748-9326/8/i=3/a=034032?key=crossref.8f60cb76b3324084849e22201ba879bf.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophys. Res. Lett.*, **35**, L20405, doi:10.1029/2008GL035258. http://doi.wiley.com/10.1029/2008GL035258.

Gleick, P. H., and M. Heberger, 2014: Water and Conflict. Events, Trends, and Analysis (2011-2012). *The World's Water. The Biennial Report on Freshwater Resources. Volume 8*, P.H. Gleick, Ed., Island Press, 159–172.

Gourdji, S. M., A. M. Sibley, and D. B. Lobell, 2013: Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environ. Res. Lett.*, **8**, 24041, doi:10.1088/1748-9326/8/2/024041. http://stacks.iop.org/1748-9326/8/i=2/a=024041?key=crossref.71d4bd7d0045166be569277634403f63.

Graham, R. W., and Coauthors, 2016: Timing and causes of mid-Holocene mammoth extinction on St. Paul Island, Alaska. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, 9310–9314, doi:10.1073/pnas.1604903113.

Graux, A.-I., G. Bellocchi, R. Lardy, and J.-F. Soussana, 2013: Ensemble modelling of climate change risks and opportunities for managed grasslands in France. *Agric. For. Meteorol.*, **170**, 114–131, doi:10.1016/j.agrformet.2012.06.010. http://www.sciencedirect.com/science/article/pii/S0168192312002092.

Gregory, P. J., and B. Marshall, 2012: Attribution of climate change: a methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. *Glob. Chang. Biol.*, **18**, 1372–1388,

doi:10.1111/j.1365-2486.2011.02601.x. http://doi.wiley.com/10.1111/j.1365-2486.2011.02601.x.
Greve, P., and S. I. Seneviratne, 2015: Assessment of future changes in water availability and aridity. *Geophys. Res. Lett.*, **42**, 5493–5499, doi:10.1002/2015GL064127. http://doi.wiley.com/10.1002/2015GL064127.
Greve, P., B. Orlowsky, B. Mueller, J. Sheffield, M. Reichstein, and S. I. Seneviratne, 2014: Global assessment of trends in wetting and drying over land. *Nat. Geosci.*, **7**, 716–721, doi:10.1038/ngeo2247. http://www.nature.com/doifinder/10.1038/ngeo2247.
Grossman-Clarke, S., S. Schubert, and D. Fenner, 2017: Urban effects on summertime air temperature in Germany under climate change. *Int. J. Climatol.*, **37**, 905–917, doi:10.1002/joc.4748. http://doi.wiley.com/10.1002/joc.4748.
Gu, G., and R. F. Adler, 2013: Interdecadal variability/long-term changes in global precipitation patterns during the past three decades: global warming and/or pacific decadal variability? *Clim. Dyn.*, **40**, 3009–3022, doi:10.1007/s00382-012-1443-8. http://link.springer.com/10.1007/s00382-012-1443-8.
Gu, G., and R. F. Adler, 2015: Spatial Patterns of Global Precipitation Change and Variability during 1901–2010. *J. Clim.*, **28**, 4431–4453, doi:10.1175/JCLI-D-14-00201.1. http://journals.ametsoc.org/doi/10.1175/JCLI-D-14-00201.1.
Guiot, J., and W. Cramer, 2016: Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science (80-.).*, **354**, 465 LP-- 468. http://science.sciencemag.org/content/354/6311/465.abstract.
Guis, H., C. Caminade, C. Calvete, A. P. Morse, A. Tran, and M. Baylis, 2012: Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe. *J. R. Soc. Interface*, **9**, 339–350, doi:10.1098/rsif.2011.0255. http://www.ncbi.nlm.nih.gov/pubmed/21697167.
Gynther, I., Waller, N. & Leung, L. K.-P., 2016: *Confirmation of the extinction of the Bramble Cay melomys Melomys rubicola on Bramble Cay, Torres Strait: results and conclusions from a comprehensive survey in August–September 2014*. Brisbane,.
Hall, A., and X. Qu, 2006: Using the current seasonal cycle to constrain snow albedo feedback in future climate change. *Geophys. Res. Lett.*, **33**, L03502, doi:10.1029/2005GL025127. http://doi.wiley.com/10.1029/2005GL025127.
Hamdi, R., F. Duchêne, J. Berckmans, A. Delcloo, C. Vanpoucke, and P. Termonia, 2016: Evolution of urban heat wave intensity for the Brussels Capital Region in the ARPEGE-Climat A1B scenario. *Urban Clim.*, **17**, 176–195, doi:10.1016/j.uclim.2016.08.001. http://linkinghub.elsevier.com/retrieve/pii/S2212095516300323.
Hamdi, R., O. Giot, R. De Troch, A. Deckmyn, and P. Termonia, 2015: Future climate of Brussels and Paris for the 2050s under the A1B scenario. *Urban Clim.*, **12**, 160–182, doi:10.1016/j.uclim.2015.03.003. http://linkinghub.elsevier.com/retrieve/pii/S2212095515000097.
Han, J.-Y., J.-J. Baik, and H. Lee, 2014: Urban impacts on precipitation. *Asia-Pacific J. Atmos. Sci.*, **50**, 17–30, doi:10.1007/s13143-014-0016-7. http://link.springer.com/10.1007/s13143-014-0016-7.
Hanasaki, N., and Coauthors, 2013: A global water scarcity assessment under Shared Socio-economic Pathways {&}ndash; Part 2: Water availability and scarcity. *Hydrol. Earth Syst. Sci.*, **17**, 2393–2413, doi:10.5194/hess-17-2393-2013. http://www.hydrol-earth-syst-sci.net/17/2393/2013/.
Handmer, J., and Coauthors, 2012: Changes in Impacts of Climate Extremes: Human Systems and Ecosystems. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 231–290 https://www.ipcc.ch/pdf/special-reports/srex/SREX-Chap4%7B_%7DFINAL.pdf.
Hansen, J., M. Sato, and R. Ruedy, 2012: Perception of climate change. *Proc. Natl. Acad. Sci. U. S. A.*, **109**, E2415--23, doi:10.1073/pnas.1205276109. http://www.ncbi.nlm.nih.gov/pubmed/22869707.
Hartmann, D. L., and Coauthors, 2013: Observations: Atmosphere and Surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Harvey, C. A., and Coauthors, 2014: Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conserv. Lett.*, **7**, 77–90, doi:10.1111/conl.12066. http://doi.wiley.com/10.1111/conl.12066.
Hasselmann, K., 2013: Detecting and responding to climate change. *Tellus B*, **1**, 1–16, doi:http://dx.doi.org/10.3402/tellusb.v65i0.20088 1. http://blog.global-systems-science.eu/wp-content/uploads/2012/12/D%7B_%7Dand%7B_%7DR%7B_%7D2%7B_%7Dsingle-line.pdf.
Hatfield, J. L., K. J. Boote, B. A. Kimball, L. H. Ziska, and R. C. Izaurralde, 2011: Climate Impacts on Agriculture: Implications for Crop Production. http://digitalcommons.unl.edu/usdaarsfacpub.
Haugan, P. M., and H. Drange, 1996: Effects of CO2 on the ocean environment. *Energy Convers. Manag.*, **37**, 1019–1022, doi:10.1016/0196-8904(95)00292-8.
He, Q., and G. Zhou, 2016: Climate-associated distribution of summer maize in China from 1961 to 2010. *Agric. Ecosyst. {&} Environ.*, **232**, 326–335, doi:10.1016/j.agee.2016.08.020. http://www.sciencedirect.com/science/article/pii/S0167880916304236.
Hegerl, G. C., O. Hoegh-Guldberg, G. Casassa, M. P. Hoerling, R. S. Kovats, C. Parmesan, D. W. Pierce, and P. A.

Stott, 2010: Good Practice Guidance Paper on Detection and Attribution Related to Anthropogenic Climate Change. *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change*, S. T.F., C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M. Midgley, and K.L. Ebi, Eds., IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland http://www.ipcc-wg2.awi.de/guidancepaper/IPCC%7B_%7DD%7B&%7DA%7B_%7DGoodPracticeGuidancePaper.pdf.

Hegerl, G. C., and Coauthors, 2007: Understanding and Attributing Climate Change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hejazi, M. I., and Coauthors, 2015: 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. *Proc. Natl. Acad. Sci. U. S. A.*, **112**, 10635–10640, doi:10.1073/pnas.1421675112. http://www.ncbi.nlm.nih.gov/pubmed/26240363.

Hemer, M. A., Y. Fan, N. Mori, A. Semedo, and X. L. Wang, 2013: Projected changes in wave climate from a multi-model ensemble. *Nat. Clim. Chang.*, **3**, 471–476, doi:10.1038/nclimate1791. http://www.nature.com/doifinder/10.1038/nclimate1791.

Hemer, M. A., and C. E. Trenham, 2016: Evaluation of a CMIP5 derived dynamical global wind wave climate model ensemble. *Ocean Model.*, **103**, 190–203, doi:10.1016/j.ocemod.2015.10.009. http://www.sciencedirect.com/science/article/pii/S1463500315002127.

Herbert, E. R., and Coauthors, 2015: A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *ECOSPHERE*, **6**, doi:10.1890/ES14-00534.1.

Hidalgo, H. G., and Coauthors, 2009: Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States. *J. Clim.*, **22**, 3838–3855, doi:10.1175/2009JCLI2470.1. http://journals.ametsoc.org/doi/abs/10.1175/2009JCLI2470.1.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae, 2013: Global flood risk under climate change. *Nat. Clim. Chang.*, **3**, 816–821, doi:10.1038/nclimate1911. http://www.nature.com/doifinder/10.1038/nclimate1911.

Hirsch, A. L., M. Wilhelm, E. L. Davin, W. Thiery, and S. I. Seneviratne, 2017: Can climate-effective land management reduce regional warming? *J. Geophys. Res. Atmos.*, **122**, 2269–2288, doi:10.1002/2016JD026125. http://doi.wiley.com/10.1002/2016JD026125.

Hoegh-Guldberg, O., and Coauthors, 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science (80-.).*, **318**. http://science.sciencemag.org/content/318/5857/1737.

Holland, G., and C. L. Bruyère, 2014: Recent intense hurricane response to global climate change. *Clim. Dyn.*, **42**, 617–627, doi:10.1007/s00382-013-1713-0. http://link.springer.com/10.1007/s00382-013-1713-0.

Holmgren, K., A. Gogou, A. Izdebski, J. Luterbacher, M. A. Sicre, and E. Xoplaki, 2016: Mediterranean Holocene climate, environment and human societies. *Quat. Sci. Rev.*, **136**, doi:10.1016/j.quascirev.2015.12.014.

Honish, B., and Coauthors, 2012: The geological record of ocean acidification. *Science (80-.).*, **335**, 1058–1063, doi:10.1126/science.1208277. http://www.sciencemag.org/content/335/6072/1058.abstract.

Huang, S., V. Krysanova, and F. Hattermann, 2015: Projections of climate change impacts on floods and droughts in Germany using an ensemble of climate change scenarios. *Reg. Environ. Chang.*, **15**, 461–473, doi:10.1007/s10113-014-0606-z. http://link.springer.com/10.1007/s10113-014-0606-z.

Huang, Z., B. Liu, M. Davis, J. Sardans, J. Peñuelas, and S. Billings, 2016: Long-term nitrogen deposition linked to reduced water use efficiency in forests with low phosphorus availability. *New Phytol.*, **210**, 431–442, doi:10.1111/nph.13785.

Imhoff, M. L., P. Zhang, R. E. Wolfe, and L. Bounoua, 2010: Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sens. Environ.*, **114**, 504–513, doi:10.1016/j.rse.2009.10.008. http://www.sciencedirect.com/science/article/pii/S0034425709003174.

Ingham, A., J. Ma, and A. M. Ulph, 2013: Can adaptation and mitigation be complements? *Clim. Change*, **120**, 39–53, doi:10.1007/s10584-013-0815-3. http://link.springer.com/10.1007/s10584-013-0815-3.

IPCC, 2013: *Climate Change 2013 The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Edited by*. T.F. Stocker et al., Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5%7B_%7DFrontmatter%7B_%7DFINAL.pdf.

IPCC, 2007: *Climate Change 2007 The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-frontmatter.pdf.

Izaurralde, R. C., A. M. Thomson, J. A. Morgan, P. A. Fay, H. W. Polley, and J. L. Hatfield, 2011: Climate Impacts on Agriculture: Implications for Forage and Rangeland Production. *Agron. J.*, **103**, 371,

doi:10.2134/agronj2010.0304. https://www.agronomy.org/publications/aj/abstracts/103/2/371.
Jacob, D., and Coauthors, 2014: EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Chang.*, **14**, 563–578, doi:10.1007/s10113-013-0499-2. http://link.springer.com/10.1007/s10113-013-0499-2.
Jacob, M., A. Frankl, H. Beeckman, G. Mesfin, M. Hendrickx, E. Guyassa, and J. Nyssen, 2015: North Ethiopian Afro-Alpine Tree Line Dynamics and Forest-Cover Change Since the Early 20th Century. *L. Degrad. {&} Dev.*, **26**, 654–664, doi:10.1002/ldr.2320.
JAGGARD, K. W., A. QI, and M. A. SEMENOV, 2007: The impact of climate change on sugarbeet yield in the UK: 1976–2004. *J. Agric. Sci.*, **145**, 367, doi:10.1017/S0021859607006922. http://www.journals.cambridge.org/abstract%7B_%7DS0021859607006922.
James, R., R. Washington, C.-F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdiscip. Rev. Clim. Chang.*, doi:10.1002/wcc.457. http://doi.wiley.com/10.1002/wcc.457.
Jeong, S.-J., C.-H. Ho, S. Piao, J. Kim, P. Ciais, Y.-B. Lee, J.-G. Jhun, and S. K. Park, 2014: Effects of double cropping on summer climate of the North China Plain and neighbouring regions. *Nat. Clim. Chang.*, **4**, 615–619, doi:10.1038/nclimate2266. http://www.nature.com/doifinder/10.1038/nclimate2266.
Jiang, C., and F. Wang, 2016: Temporal changes of streamflow and its causes in the Liao River Basin over the period of 1953–2011, northeastern China. *CATENA*, **145**, 227–238, doi:10.1016/j.catena.2016.06.015. http://www.sciencedirect.com/science/article/pii/S0341816216302211.
Jiang, D., and Z. Tian, 2013: East Asian monsoon change for the 21st century: Results of CMIP3 and CMIP5 models. *Chinese Sci. Bull.*, **58**, 1427–1435, doi:10.1007/s11434-012-5533-0. http://link.springer.com/10.1007/s11434-012-5533-0.
Jiang, Y., Q. Zhuang, S. Sitch, J. A. O'Donnell, D. Kicklighter, A. Sokolov, and J. Melillo, 2016: Importance of soil thermal regime in terrestrial ecosystem carbon dynamics in the circumpolar north. *Glob. Planet. Change*, **142**, 28–40, doi:10.1016/j.gloplacha.2016.04.011.
Jiao, M., G. Zhou, and Z. Chen, eds., 2014: *Blue book of agriculture for addressing climate change: Assessment report of climatic change impacts on agriculture in China (No.1)*. Social Sciences Academic Press, Beiging,.
Jiao, M., G. Zhou, and Z. Zhang, eds., 2016: *Blue book of agriculture for addressing climate change: Assessment report of agro-meteorological disasters and yield losses in China (No.2)*. Social Sciences Academic Press, Beijing,.
Jonas, M., G. Marland, V. Krey, F. Wagner, and Z. Nahorski, 2014: Uncertainty in an emissions-constrained world. *Clim. Change*, **124**, 459–476, doi:10.1007/s10584-014-1103-6. http://link.springer.com/10.1007/s10584-014-1103-6.
Jones, C. D., and Coauthors, 2016: Simulating the Earth system response to negative emissions. *Environ. Res. Lett.*, **11**, 95012, doi:10.1088/1748-9326/11/9/095012. http://stacks.iop.org/1748-9326/11/i=9/a=095012?key=crossref.6b5747055a178d1c59ffa940adb33091.
Jones, C., L. M. V Carvalho, C. Jones, and L. M. V Carvalho, 2013: Climate Change in the South American Monsoon System: Present Climate and CMIP5 Projections. *J. Clim.*, **26**, 6660–6678, doi:10.1175/JCLI-D-12-00412.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00412.1.
Kaiser, K., P. J. Koch, R. Mauersberger, P. Stüve, J. Dreibrodt, and O. Bens, 2014: Detection and attribution of lake-level dynamics in north-eastern central Europe in recent decades. *Reg. Environ. Chang.*, **14**, 1587–1600, doi:10.1007/s10113-014-0600-5. http://link.springer.com/10.1007/s10113-014-0600-5.
Kang, N.-Y., and J. B. Elsner, 2015: Trade-off between intensity and frequency of global tropical cyclones. *Nat. Clim. Chang.*, **5**, 661–664, doi:10.1038/nclimate2646. http://www.nature.com/doifinder/10.1038/nclimate2646.
Kaniewski, D., J. Guiot, and E. Van Campo, 2015: Drought and societal collapse 3200years ago in the Eastern Mediterranean: A review. *Wiley Interdiscip. Rev. Clim. Chang.*, **6**, 369–382, doi:10.1002/wcc.345. http://doi.wiley.com/10.1002/wcc.345.
Kaniewski, D., J. Guiot, and E. Van Campo, 2015: Drought and societal collapse 3200 years ago in the Eastern Mediterranean: a review. *Wiley Interdiscip. Rev. Clim. Chang.*, **6**, 369–382, doi:10.1002/wcc.345. http://doi.wiley.com/10.1002/wcc.345.
Karl, T. R., and Coauthors, 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science (80-.).*, **348**. http://science.sciencemag.org/content/348/6242/1469.
Katz, R. W., M. B. Parlange, and P. Naveau, 2002: Statistics of extremes in hydrology. *Adv. Water Resour.*, **25**, 1287–1304, doi:10.1016/S0309-1708(02)00056-8. http://linkinghub.elsevier.com/retrieve/pii/S0309170802000568.
Keenan, R. J., 2015: Climate change impacts and adaptation in forest management: a review. *Ann. For. Sci.*, **72**, 145–167, doi:10.1007/s13595-014-0446-5.
Keirans, J. E., and Coauthors, 1996: Ixodes (Ixodes) scapularis (Acari: Ixodidae): Redescription of all Active Stages, Distribution, Hosts, Geographical Variation, and Medical and Veterinary Importance. *J. Med. Entomol.*, **33**, 297–318, doi:10.1093/jmedent/33.3.297. https://academic.oup.com/jme/article-lookup/doi/10.1093/jmedent/33.3.297.
Kelley, C. P., S. Mohtadi, M. A. Cane, R. Seager, and Y. Kushnir, 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Natl. Acad. Sci. U. S. A.*, **112**, 3241–3246,

doi:10.1073/pnas.1421533112. http://www.ncbi.nlm.nih.gov/pubmed/25733898.
Kendon, E. J., N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, and C. A. Senior, 2014: Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Chang.*, **4**, 570–576, doi:10.1038/nclimate2258. http://www.nature.com/doifinder/10.1038/nclimate2258.
Kingston, D. G., and R. G. Taylor, 2010: Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. *Hydrol. Earth Syst. Sci.*, **14**, 1297–1308, doi:10.5194/hess-14-1297-2010. http://www.hydrol-earth-syst-sci.net/14/1297/2010/.
Kinoshita, Y., M. Tanoue, S. Watanabe, and Y. Hirabayashi, Quantifying the effect of autonomous adaptation to global river flood projections: Application for the future flood risk assessment. *submitted*,.
Kirtman, B., and Coauthors, 2013: Near-term Climate Change: Projections and Predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, S. T.F. et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5%7B_%7DChapter11%7B_%7DFINAL.pdf.
Knutson, T. R., and Coauthors, 2010: Tropical cyclones and climate change. *Nat. Geosci.*, **3**, 157–163, doi:10.1038/ngeo779. http://www.nature.com/doifinder/10.1038/ngeo779.
Koffi, J. K., P. A. Leighton, Y. Pelcat, L. Trudel, L. R. Lindsay, F. Milord, and N. H. Ogden, 2012: Passive Surveillance for I. scapularis Ticks: Enhanced Analysis for Early Detection of Emerging Lyme Disease Risk. *J. Med. Entomol.*, **49**, 400–409, doi:10.1603/ME11210. https://academic.oup.com/jme/article-lookup/doi/10.1603/ME11210.
Koirala, S., Y. Hirabayashi, R. Mahendran, and S. Kanae, 2014: Global assessment of agreement among streamflow projections using CMIP5 model outputs. *Environ. Res. Lett.*, **9**, 64017, doi:10.1088/1748-9326/9/6/064017. http://stacks.iop.org/1748-9326/9/i=6/a=064017?key=crossref.6e3a257ffd2a2f8db6ea4f59456f51f1.
Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349–352, doi:10.1038/nature13278. http://www.nature.com/doifinder/10.1038/nature13278.
Kossin, J. P., T. L. Olander, K. R. Knapp, J. P. Kossin, T. L. Olander, and K. R. Knapp, 2013: Trend Analysis with a New Global Record of Tropical Cyclone Intensity. *J. Clim.*, **26**, 9960–9976, doi:10.1175/JCLI-D-13-00262.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-13-00262.1.
Koster, R. D., and Coauthors, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation. *Science (80-.).*, **305**. http://science.sciencemag.org/content/305/5687/1138.
Kovach, R. P., C. C. Muhlfeld, R. Al-Chokhachy, J. B. Dunham, B. H. Letcher, and J. L. Kershner, 2016: Impacts of climatic variation on trout: a global synthesis and path forward. *Rev. FISH Biol. Fish.*, **26**, 135–151, doi:10.1007/s11160-015-9414-x.
Kroeker, K. J., R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte, and J. P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Glob. Chang. Biol.*, **19**, 1884–1896, doi:10.1111/gcb.12179.
Kusaka, H., A. Suzuki-Parker, T. Aoyagi, S. A. Adachi, and Y. Yamagata, 2016: Assessment of RCM and urban scenarios uncertainties in the climate projections for August in the 2050s in Tokyo. *Clim. Change*, **137**, 427–438, doi:10.1007/s10584-016-1693-2. http://link.springer.com/10.1007/s10584-016-1693-2.
Kuttler, W., 2012: Climate Change on the Urban Scale – Effects and Counter-Measures in Central Europe. *Human and Social Dimensions of Climate Change*, InTech http://www.intechopen.com/books/human-and-social-dimensions-of-climate-change/climate-change-on-the-urban-scale-effects-and-counter-measures-in-central-europe.
Last, P. R., W. T. White, D. C. Gledhill, A. J. Hobday, R. Brown, G. J. Edgar, and G. Pecl, 2011: Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Glob. Ecol. Biogeogr.*, **20**, 58–72, doi:10.1111/j.1466-8238.2010.00575.x. http://doi.wiley.com/10.1111/j.1466-8238.2010.00575.x.
Lawrence, P. J., and Coauthors, 2012: Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *J. Clim.*, **25**, 3071–3095, doi:10.1175/JCLI-D-11-00256.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-11-00256.1.
Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. . Prathe, 2007: Historical Overview of Climate Change. *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf.
Leemans, R., and B. Eickhout, 2004: Another reason for concern: regional and global impacts on ecosystems for different levels of climate change. *Glob. Environ. Chang.*, **14**, 219–228, doi:10.1016/j.gloenvcha.2004.04.009. http://www.sciencedirect.com/science/article/pii/S0959378004000391.

Leighton, P. A., J. K. Koffi, Y. Pelcat, L. R. Lindsay, and N. H. Ogden, 2012: Predicting the speed of tick invasion: an empirical model of range expansion for the Lyme disease vector {<}i{>}Ixodes scapularis{<}/i{>} in Canada. *J. Appl. Ecol.*, **49**, 457–464, doi:10.1111/j.1365-2664.2012.02112.x. http://doi.wiley.com/10.1111/j.1365-2664.2012.02112.x.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. U. S. A.*, **105**, 1786–1793, doi:10.1073/pnas.0705414105. http://www.ncbi.nlm.nih.gov/pubmed/18258748.

Lewandowsky, S., J. S. Risbey, N. Oreskes, S. Lewandowsky, J. S. Risbey, and N. Oreskes, 2016: The "Pause" in Global Warming: Turning a Routine Fluctuation into a Problem for Science. *http://dx.doi.org/10.1175/BAMS-D-14-00106.1*, doi:10.1175/BAMS-D-14-00106.1. http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-14-00106.1.

Li, D., E. Bou-Zeid, D. Li, and E. Bou-Zeid, 2013: Synergistic Interactions between Urban Heat Islands and Heat Waves: The Impact in Cities Is Larger than the Sum of Its Parts*. *J. Appl. Meteorol. Climatol.*, **52**, 2051–2064, doi:10.1175/JAMC-D-13-02.1. http://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-13-02.1.

Li, Z., and H. Fang, 2016: Impacts of climate change on water erosion: A review. *Earth-Science Rev.*, **163**, 94–117, doi:10.1016/j.earscirev.2016.10.004. http://www.sciencedirect.com/science/article/pii/S0012825216303555.

Liu, L., X. Zhang, A. Donnelly, and X. Liu, 2016: Interannual variations in spring phenology and their response to climate change across the Tibetan Plateau from 1982 to 2013. *Int. J. Biometeorol.*, **60**, 1563–1575, doi:10.1007/s00484-016-1147-6.

Liu, Q., and Coauthors, 2016: Wind and Wave Climate in the Arctic Ocean as Observed by Altimeters. *J. Clim.*, **29**, 7957–7975, doi:10.1175/JCLI-D-16-0219.1. http://journals.ametsoc.org/doi/10.1175/JCLI-D-16-0219.1.

Lluch-Cota, S. E., O. Hoegh-Guldberg, D. M. Karl, H. O. Pörtner, S. Sundby, and J. P. Gattuso, 2014: Cross-chapter box on uncertain trends in major upwelling ecosystems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*.

Lobell, D. B., G. Bala, and P. B. Duffy, 2006: Biogeophysical impacts of cropland management changes on climate. *Geophys. Res. Lett.*, **33**, L06708, doi:10.1029/2005GL025492. http://doi.wiley.com/10.1029/2005GL025492.

Lobell, D. B., M. J. Roberts, W. Schlenker, N. Braun, B. B. Little, R. M. Rejesus, and G. L. Hammer, 2014: Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. *Science (80-.).*, **344**, 516–519, doi:10.1126/science.1251423. http://www.sciencemag.org/cgi/doi/10.1126/science.1251423.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts, 2011: Climate Trends and Global Crop Production Since 1980. *Science (80-.).*, **333**. http://science.sciencemag.org/content/333/6042/616.

Lobell, D., and Coauthors, 2009: Regional Differences in the Influence of Irrigation on Climate. *J. Clim.*, **22**, 2248–2255, doi:10.1175/2008JCLI2703.1. http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2703.1.

Lockwood, J. G., 2001: Abrupt and sudden climatic transitions and fluctuations: A review. *Int. J. Climatol.*, **21**, 1153–1179, doi:10.1002/joc.630.

Lorenzen, E. D., and Coauthors, 2011: Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature*, **479**, 359–364, doi:10.1038/nature10574. http://dx.doi.org/10.1038/nature10574%7B%25%7D5Cnhttp://www.nature.com/doifinder/10.1038/nature10574.

LU, X. X., L. S. RAN, S. LIU, T. JIANG, S. R. ZHANG, and J. J. WANG, 2013: Sediment loads response to climate change: A preliminary study of eight large Chinese rivers. *Int. J. Sediment Res.*, **28**, 1–14, doi:10.1016/S1001-6279(13)60013-X. http://linkinghub.elsevier.com/retrieve/pii/S100162791360013X.

Lü, X., G. Zhou, Y. Wang, and X. Song, 2016: Effects of changing precipitation and warming on functional traits of zonal Stipa plants from Inner Mongolian grassland. *J. Meteorol. Res.*, **30**, 412–425, doi:10.1007/s13351-016-5091-5. http://link.springer.com/10.1007/s13351-016-5091-5.

Luderer, G., R. C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, and O. Edenhofer, 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033, doi:10.1088/1748-9326/8/3/034033. http://stacks.iop.org/1748-9326/8/i=3/a=034033?key=crossref.68299324c711aa38b9eb1d10cb1df7ec.

Luo, K., F. Tao, J. P. Moiwo, D. Xiao, and J. Zhang, 2016: Attribution of hydrological change in Heihe River Basin to climate and land use change in the past three decades. *Sci. Rep.*, **6**, 33704, doi:10.1038/srep33704. http://www.nature.com/articles/srep33704.

Luyssaert, S., and Coauthors, 2014: Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Clim. Chang.*, **4**, 389–393, doi:10.1038/nclimate2196. http://www.nature.com/doifinder/10.1038/nclimate2196.

Ma, J., G. R. Foltz, B. J. Soden, G. Huang, J. He, and C. Dong, 2016: Will surface winds weaken in response to global warming? *Environ. Res. Lett.*, **11**, 124012, doi:10.1088/1748-9326/11/12/124012. http://stacks.iop.org/1748-9326/11/i=12/a=124012?key=crossref.8f448e097bb8e4878a677e67ede38379.

Mahlstein, I., R. Knutti, S. Solomon, and R. W. Portmann, 2011: Early onset of significant local warming in low latitude countries. *Environ. Res. Lett.*, **6**, 34009, doi:10.1088/1748-9326/6/3/034009. http://stacks.iop.org/1748-

9326/6/i=3/a=034009?key=crossref.4f6f298120b5f9acd1127c399bd39515.
Mallakpour, I., and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nat. Clim. Chang.*, **5**, 250–254, doi:10.1038/nclimate2516. http://www.nature.com/doifinder/10.1038/nclimate2516.
Marshall, B. E., 2012: Does climate change really explain changes in the fisheries productivity of Lake Kariba (Zambia-Zimbabwe)? *Trans. R. Soc. South Africa*, **67**, 45–51, doi:10.1080/0035919X.2012.694083. http://www.tandfonline.com/doi/abs/10.1080/0035919X.2012.694083.
Marszelewski, W., and B. Pius, 2016: Long-term changes in temperature of river waters in the transitional zone of the temperate climate: a case study of Polish rivers. *Hydrol. Sci. J.*, **61**, 1430–1442, doi:10.1080/02626667.2015.1040800. http://www.tandfonline.com/doi/full/10.1080/02626667.2015.1040800.
Masike, S., and P. Urich, 2008: Vulnerability of traditional beef sector to drought and the challenges of climate change: The case of Kgatleng District, Botswana. **1**, 12–18. http://researchcommons.waikato.ac.nz/handle/10289/973.
Mathis, J. T., and Coauthors, 2015: Ocean acidification risk assessment for Alaska's fishery sector. *Prog. Oceanogr.*, **136**, 71–91, doi:10.1016/j.pocean.2014.07.001. http://dx.doi.org/10.1016/j.pocean.2014.07.001.
Mbow, C., P. Smith, D. Skole, L. Duguma, and M. Bustamante, 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 8–14, doi:10.1016/j.cosust.2013.09.002. http://linkinghub.elsevier.com/retrieve/pii/S1877343513001255.
Mbow, C., M. Van Noordwijk, E. Luedeling, H. Neufeldt, P. A. Minang, and G. Kowero, 2014: Agroforestry solutions to address food security and climate change challenges in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 61–67, doi:10.1016/j.cosust.2013.10.014. http://linkinghub.elsevier.com/retrieve/pii/S1877343513001449.
Mbow, C., M. van Noordwijk, R. Prabhu, and T. Simons, 2014: Knowledge gaps and research needs concerning agroforestry's contribution to Sustainable Development Goals in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 162–170, doi:10.1016/j.cosust.2013.11.030. http://linkinghub.elsevier.com/retrieve/pii/S1877343513001929.
McCarthy, M. P., M. J. Best, and R. A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophys. Res. Lett.*, **37**, n/a--n/a, doi:10.1029/2010GL042845. http://doi.wiley.com/10.1029/2010GL042845.
McInnes, K. L., T. A. Erwin, and J. M. Bathols, 2011: Global Climate Model projected changes in 10 m wind speed and direction due to anthropogenic climate change. *Atmos. Sci. Lett.*, **12**, 325–333, doi:10.1002/asl.341. http://doi.wiley.com/10.1002/asl.341.
McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardulli, and R. J. Donohue, 2008: Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophys. Res. Lett.*, **35**, L20403, doi:10.1029/2008GL035627. http://doi.wiley.com/10.1029/2008GL035627.
Médail, F., 2017: The specific vulnerability of plant biodiversity and vegetation on Mediterranean islands in the face of global change. *Reg. Environ. Chang.*, 1–16, doi:10.1007/s10113-017-1123-7. http://link.springer.com/10.1007/s10113-017-1123-7.
Mekonnen, A., 2014: Economic Costs of Climate Change and Climate Finance with a Focus on Africa. *J. Afr. Econ.*, **23**, ii50--ii82, doi:10.1093/jae/eju012. https://academic.oup.com/jae/article-lookup/doi/10.1093/jae/eju012.
Melkonyan, A., and P. Wagner, 2013: Ozone and its projection in regard to climate change. *Atmos. Environ.*, **67**, 287–295, doi:10.1016/j.atmosenv.2012.10.023. http://linkinghub.elsevier.com/retrieve/pii/S1352231012009879.
Min, S.-K., X. Zhang, F. W. Zwiers, and G. C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470**, 378–381, doi:10.1038/nature09763. http://www.ncbi.nlm.nih.gov/pubmed/21331039.
Mirzaei, P. A., and F. Haghighat, 2010: Approaches to study Urban Heat Island – Abilities and limitations. *Build. Environ.*, **45**, 2192–2201, doi:10.1016/j.buildenv.2010.04.001. http://www.sciencedirect.com/science/article/pii/S0360132310001083.
Mitchell, D., and Coauthors, 2017: Half a degree additional warming, prognosis and projected impacts (HAPPI): background and experimental design. *Geosci. Model Dev*, **10**, 571–583, doi:10.5194/gmd-10-571-2017. www.geosci-model-dev.net/10/571/2017/.
Mitchell, D., and Coauthors, 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environ. Res. Lett.*, **11**, 74006, doi:10.1088/1748-9326/11/7/074006. http://stacks.iop.org/1748-9326/11/i=7/a=074006?key=crossref.6e5075a68a4ec09357b8e361a9871511.
Mitchell, D., and D. Mitchell, 2016: Human Influences on Heat-Related Health Indicators During the 2015 Egyptian Heat Wave. *Bull. Am. Meteorol. Soc.*, **97**, S70--S74, doi:10.1175/BAMS-D-16-0132.1. http://journals.ametsoc.org/doi/10.1175/BAMS-D-16-0132.1.
Monier, E., and X. Gao, 2015: Climate change impacts on extreme events in the United States: an uncertainty analysis. *Clim. Change*, **131**, 67–81, doi:10.1007/s10584-013-1048-1. http://link.springer.com/10.1007/s10584-013-1048-1.
Montaldo, N., and R. Oren, 2016: The way the wind blows matters to ecosystem water use efficiency. *Agric. For. Meteorol.*, **217**, 1–9, doi:10.1016/j.agrformet.2015.11.002.
Moriondo, M., G. V Jones, B. Bois, C. Dibari, R. Ferrise, G. Trombi, and M. Bindi, 2013: Projected shifts of wine regions in response to climate change. *Clim. Change*, **119**, 825–839, doi:10.1007/s10584-013-0739-y. http://link.springer.com/10.1007/s10584-013-0739-y.

Moriondo, M., G. Trombi, R. Ferrise, G. Brandani, C. Dibari, C. M. Ammann, M. M. Lippi, and M. Bindi, 2013: Olive trees as bio-indicators of climate evolution in the Mediterranean Basin. *Glob. Ecol. Biogeogr.*, **22**, 818–833, doi:10.1111/geb.12061. http://doi.wiley.com/10.1111/geb.12061.
Mortensen, C. J., Y. H. Choi, K. Hinrichs, N. H. Ing, D. C. Kraemer, S. G. Vogelsang, and M. M. Vogelsang, 2009: Embryo recovery from exercised mares. *Anim. Reprod. Sci.*, **110**, 237–244, doi:10.1016/j.anireprosci.2008.01.015. http://www.sciencedirect.com/science/article/pii/S0378432008000298.
Mortensen, L. O., E. Jeppesen, N. M. Schmidt, K. S. Christoffersen, M. P. Tamstorf, and M. C. Forchhammer, 2014: Temporal trends and variability in a high-arctic ecosystem in Greenland: multidimensional analyses of limnic and terrestrial ecosystems. *Polar Biol.*, **37**, 1073–1082, doi:10.1007/s00300-014-1501-2.
Morton, J. F., W. Solecki, P. Dasgupta, D. Dodman, and M. G. Rivera-Ferre, 2014: Cross-chapter box on urban–rural interactions—context for climate change vulnerability, impacts, and adaptation. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 153–155.
Mourato, S., M. Moreira, and J. Corte-Real, 2009: Interannual variability of precipitation distribution patterns in Southern Portugal. *Int. J. Climatol.*, **30**, n/a--n/a, doi:10.1002/joc.2021. http://doi.wiley.com/10.1002/joc.2021.
Mourato, S., M. Moreira, and J. Corte-Real, 2015: Water Resources Impact Assessment Under Climate Change Scenarios in Mediterranean Watersheds. *Water Resour. Manag.*, **29**, 2377–2391, doi:10.1007/s11269-015-0947-5. http://link.springer.com/10.1007/s11269-015-0947-5.
Moxnes, E., 1998: Not Only the Tragedy of the Commons: Misperceptions of Bioeconomics. *Manage. Sci.*, **44**, 1234–1248, doi:10.1287/mnsc.44.9.1234.
Moxnes, E., and A. K. Saysel, 2009: Misperceptions of global climate change: Information policies. *Clim. Change*, **93**, 15–37, doi:10.1007/s10584-008-9465-2.
Mueller, B., M. Hauser, C. Iles, R. H. Rimi, F. W. Zwiers, and H. Wan, 2015: Lengthening of the growing season in wheat and maize producing regions. *Weather Clim. Extrem.*, **9**, 47–56, doi:10.1016/j.wace.2015.04.001. http://linkinghub.elsevier.com/retrieve/pii/S2212094715000183.
Mueller, B., and S. I. Seneviratne, 2012: Hot days induced by precipitation deficits at the global scale. *Proc. Natl. Acad. Sci. U. S. A.*, **109**, 12398–12403, doi:10.1073/pnas.1204330109. http://www.ncbi.nlm.nih.gov/pubmed/22802672.
Mueller, N. D., E. E. Butler, K. A. McKinnon, A. Rhines, M. Tingley, N. M. Holbrook, and P. Huybers, 2015: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nat. Clim. Chang.*, **6**, 317–322, doi:10.1038/nclimate2825. http://www.nature.com/doifinder/10.1038/nclimate2825.
Müller, N., W. Kuttler, and A.-B. Barlag, 2014: Counteracting urban climate change: adaptation measures and their effect on thermal comfort. *Theor. Appl. Climatol.*, **115**, 243–257, doi:10.1007/s00704-013-0890-4. http://link.springer.com/10.1007/s00704-013-0890-4.
Munoz-Rojas, M., W. Lewandrowski, T. E. Erickson, K. W. Dixon, and D. J. Merritt, 2016: Soil respiration dynamics in fire affected semi-arid ecosystems: Effects of vegetation type and environmental factors. *Sci. Total Environ.*, **572**, 1385–1394, doi:10.1016/j.scitotenv.2016.02.086.
Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environ. Res. Lett.*, **11**, 95004, doi:10.1088/1748-9326/11/9/095004. http://stacks.iop.org/1748-9326/11/i=9/a=095004?key=crossref.962cb328d4e5c48882928ffcb3cdc7fe.
Murphy, G. E. P., and T. N. Romanuk, 2016: Data gaps in anthropogenically driven local-scale species richness change studies across the Earth's terrestrial biomes. *Ecol. Evol.*, **6**, 2938–2947, doi:10.1002/ece3.2004.
Murphy, G. E. P., and T. N. Romanuk, 2014: A meta-analysis of declines in local species richness from human disturbances. *Ecol. Evol.*, **4**, 91–103, doi:10.1002/ece3.909.
Murray-Tortarolo, G., and Coauthors, 2016: The carbon cycle in Mexico: past, present and future of C stocks and fluxes. *Biogeosciences*, **13**, 223–238, doi:10.5194/bg-13-223-2016.
Nakićenović, N., and R. Swart, eds., 2000: *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.
Nayak, S., and K. Dairaku, 2016: Future changes in extreme precipitation intensities associated with temperature under SRES A1B scenario. *Hydrol. Res. Lett.*, **10**, 139–144, doi:10.3178/hrl.10.139. https://www.jstage.jst.go.jp/article/hrl/10/4/10%7B_%7D139/%7B_%7Darticle.
Ndebele-Murisa, M. R., E. Mashonjowa, and T. Hill, 2011: The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe. *Trans. R. Soc. South Africa*, **66**, 105–119, doi:10.1080/0035919X.2011.600352. http://www.tandfonline.com/doi/abs/10.1080/0035919X.2011.600352.
Nelson, G. C., and Coauthors, 2014: Climate change effects on agriculture: economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3274–3279, doi:10.1073/pnas.1222465110. http://www.ncbi.nlm.nih.gov/pubmed/24344285.
Nordhaus, W. D., 2012: Economic Policy in the Face of Severe Tail Events. *J. Public Econ. Theory*, **14**, 197–219, doi:10.1111/j.1467-9779.2011.01544.x.

Notaro, M., Y. Yu, and O. V Kalashnikova, 2015: Regime shift in Arabian dust activity, triggered by persistent Fertile Crescent drought. *J. Geophys. Res. Atmos.*, **120**, doi:10.1002/2015JD023855. http://onlinelibrary.wiley.com/doi/10.1002/2015JD023855/full.

Ochoa, A., L. Campozano, E. Sánchez, R. Gualán, and E. Samaniego, 2016: Evaluation of downscaled estimates of monthly temperature and precipitation for a Southern Ecuador case study. *Int. J. Climatol.*, **36**, 1244–1255, doi:10.1002/joc.4418. http://doi.wiley.com/10.1002/joc.4418.

Ochoa, A., L. Pineda, P. Crespo, and P. Willems, 2014: Evaluation of TRMM 3B42 precipitation estimates and WRF retrospective precipitation simulation over the Pacific–Andean region of Ecuador and Peru. *Hydrol. Earth Syst. Sci.*, **18**, 3179–3193, doi:10.5194/hess-18-3179-2014. http://www.hydrol-earth-syst-sci.net/18/3179/2014/.

Ogden, N. H., and Coauthors, 2006: Investigation of ground level and remote-sensed data for habitat classification and prediction of survival of Ixodes scapularis in habitats of southeastern Canada. *J. Med. Entomol.*, **43**, 403–414. http://www.ncbi.nlm.nih.gov/pubmed/16619627.

Ogden, N. H., and Coauthors, 2005: A dynamic population model to investigate effects of climate on geographic range and seasonality of the tick Ixodes scapularis. *Int. J. Parasitol.*, **35**, 375–389, doi:10.1016/j.ijpara.2004.12.013. http://linkinghub.elsevier.com/retrieve/pii/S0020751905000044.

Ogden, N. H., and Coauthors, 2008: Role of migratory birds in introduction and range expansion of Ixodes scapularis ticks and of Borrelia burgdorferi and Anaplasma phagocytophilum in Canada. *Appl. Environ. Microbiol.*, **74**, 1780–1790, doi:10.1128/AEM.01982-07. http://www.ncbi.nlm.nih.gov/pubmed/18245258.

Ogden, N. H., and Coauthors, 2006: Climate change and the potential for range expansion of the Lyme disease vector Ixodes scapularis in Canada. *Int. J. Parasitol.*, **36**, 63–70, doi:10.1016/j.ijpara.2005.08.016. http://linkinghub.elsevier.com/retrieve/pii/S0020751905002985.

Ogden, N. H., and Coauthors, 2006: {<}I{>}Ixodes scapularis{<}/I{>} Ticks Collected by Passive Surveillance in Canada: Analysis of Geographic Distribution and Infection with Lyme Borreliosis Agent {<}I{>}Borrelia burgdorferi{<}/I{>}. *J. Med. Entomol.*, **43**, 600–609, doi:10.1603/0022-2585(2006)43[600:ISTCBP]2.0.CO;2. http://www.ncbi.nlm.nih.gov/pubmed/16739422.

Ogden, N., J. Koffi, L. Lindsay, S. Fleming, C. Mombourquette, D Sanford, and E. Al., 2015: *Surveillance for lyme disease in canada, 2009 to 2012. Canada Communicable Disease Report*. 41:132 pp.

Ogden, N. H., C. Bouchard, K. Kurtenbach, G. Margos, L. R. Lindsay, L. Trudel, S. Nguon, and F. Milord, 2010: Active and Passive Surveillance and Phylogenetic Analysis of Borrelia burgdorferi Elucidate the Process of Lyme Disease Risk Emergence in Canada. *Environ. Health Perspect.*, **118**, 909–914, doi:10.1289/ehp.0901766. http://www.ncbi.nlm.nih.gov/pubmed/20421192.

Ogden, N. H., M. Radojevic, X. Wu, V. R. Duvvuri, P. A. Leighton, and J. Wu, 2014: Estimated effects of projected climate change on the basic reproductive number of the Lyme disease vector Ixodes scapularis. *Environ. Health Perspect.*, **122**, 631–638, doi:10.1289/ehp.1307799. http://www.ncbi.nlm.nih.gov/pubmed/24627295.

O'Grady, J. G., K. L. McInnes, F. Colberg, M. A. Hemer, and A. V Babanin, 2015: Longshore wind, waves and currents: climate and climate projections at Ninety Mile Beach, southeastern Australia. *Int. J. Climatol.*, **35**, 4079–4093, doi:10.1002/joc.4268. http://doi.wiley.com/10.1002/joc.4268.

Okada, M., T. Iizumi, Y. Hayashi, and M. Yokozawa, 2011: Modeling the multiple effects of temperature and radiation on rice quality. *Environ. Res. Lett.*, **6**, 34031, doi:10.1088/1748-9326/6/3/034031. http://stacks.iop.org/1748-9326/6/i=3/a=034031?key=crossref.b12eda0227bafc316da25aebe5e14467.

Olesen, J. E., and Coauthors, 2011: Impacts and adaptation of European crop production systems to climate change. *Eur. J. Agron.*, **34**, 96–112, doi:10.1016/j.eja.2010.11.003. http://www.sciencedirect.com/science/article/pii/S1161030110001061.

Olhoff, A., S. Bee, and D. Puig, 2015: *The Adaptation Finance Gap Update-with insights from the INDCs*. http://web.unep.org/sites/default/files/gapreport/UNEP%7B_%7DAdaptation%7B_%7DFinance%7B_%7DGap%7B_%7DUpdate.pdf.

Olsson, L., M. Opondo, P. Tschakert, A. Agrawal, S. H. Eriksen, S. Ma, L. N. Perch, and S. A. Zakieldee, 2014: Livelihoods and poverty. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global andSectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the IntergovernmentalPanel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 793–832 http://ar5-syr.ipcc.ch/resources/htmlpdf/WGIIAR5-Chap13%7B_%7DFINAL/.

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahash, 2014: Emergent risks and key vulnerabilities. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1039–1099 http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/WGII/WGIIAR5-Chap19%7B_%7DFINAL.pdf.

Orlowsky, B., and S. I. Seneviratne, 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. *Hydrol. Earth Syst. Sci.*, **17**, 1765–1781, doi:10.5194/hess-17-1765-2013. http://www.hydrol-

earth-syst-sci.net/17/1765/2013/.
Oudin Åström, D., B. Forsberg, K. L. Ebi, and J. Rocklöv, 2013: Attributing mortality from extreme temperatures to climate change in Stockholm, Sweden. *Nat. Clim. Chang.*, **3**, 1050–1054, doi:10.1038/nclimate2022. http://dx.doi.org/10.1038/nclimate2022.
Pall, P., T. Aina, D. A. Stone, P. A. Stott, T. Nozawa, A. G. J. Hilberts, D. Lohmann, and M. R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470**, 382–385, doi:10.1038/nature09762. http://www.ncbi.nlm.nih.gov/pubmed/21331040.
Parker, C., P. Keenlyside, D. Conway, and C. Parker, 2014: Early experiences in adaptation finance: Lessons from the four multilateral climate change adaptation funds. http://www.worldwildlife.org/.
Parmesan, C., and M. E. Hanley, 2015: Plants and climate change: complexities and surprises. *Ann. Bot.*, **116**, 849–864, doi:10.1093/aob/mcv169.
Pendergrass, A. G., F. Lehner, B. M. Sanderson, and Y. Xu, 2015: Does extreme precipitation intensity depend on the emissions scenario? *Geophys. Res. Lett.*, **42**, 8767–8774, doi:10.1002/2015GL065854. http://doi.wiley.com/10.1002/2015GL065854.
Peng, S., and Coauthors, 2012: Surface Urban Heat Island Across 419 Global Big Cities. *Environ. Sci. {&} Technol.*, **46**, 696–703, doi:10.1021/es2030438. http://pubs.acs.org/doi/abs/10.1021/es2030438.
Pereira, H. M., and Coauthors, 2010: Scenarios for global biodiversity in the 21st century. *Science (80-.).*, **330**, 1496–1501, doi:10.1126/science.1196624.
Perring, M. P., B. R. Cullen, I. R. Johnson, and M. J. Hovenden, 2010: Modelled effects of rising CO2 concentration and climate change on native perennial grass and sown grass-legume pastures. *Clim. Res.*, **42**, 65–78, doi:10.3354/cr00863. http://www.int-res.com/abstracts/cr/v42/n1/p65-78/.
Pindyck, R. S., 2013: Climate Change Policy: What Do the Models Tell Us? *J. Econ. Lit.*, **51**, 1–23, doi:10.1257/jel.51.3.860. http://www.nber.org/papers/w19244.pdf.
Pittelkow, C. M., and Coauthors, 2014: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517**, 365–367, doi:10.1038/nature13809. http://dx.doi.org/10.1038/nature13809.
Porter, J. R., L. Xie, A. J. Challinor, K. Cochrane, S. M. Howden, M. M. Eqbal, D. B. Lobell, and M. I. Travasso, 2014: Food security and food production systems. *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 485–533.
Portmann, F. T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environ. Res. Lett.*, **8**, 24023, doi:10.1088/1748-9326/8/2/024023. http://stacks.iop.org/1748-9326/8/i=2/a=024023?key=crossref.b0a543a479eeff6c76b319c99956a993.
Postigo, A., 2008: Vulnerability and Adaptation to the Health Impacts of Climate Change. *Development*, **51**, 403–408, doi:10.1057/dev.2008.44. http://link.springer.com/10.1057/dev.2008.44.
Prein, A. F., and Coauthors, 2015: A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. *Rev. Geophys.*, **53**, 323–361, doi:10.1002/2014RG000475. http://doi.wiley.com/10.1002/2014RG000475.
Pryor, S. C., and R. J. Barthelmie, 2010: Climate change impacts on wind energy: A review. *Renew. Sustain. Energy Rev.*, **14**, 430–437, doi:10.1016/j.rser.2009.07.028. http://www.sciencedirect.com/science/article/pii/S1364032109001713.
Pryor, S. C., R. C. Sullivan, T. Wright, S. C. Pryor, R. C. Sullivan, and T. Wright, 2016: Quantifying the Roles of Changing Albedo, Emissivity, and Energy Partitioning in the Impact of Irrigation on Atmospheric Heat Content. *J. Appl. Meteorol. Climatol.*, **55**, 1699–1706, doi:10.1175/JAMC-D-15-0291.1. http://journals.ametsoc.org/doi/10.1175/JAMC-D-15-0291.1.
Qi, Z., and Coauthors, 2016: Vegetation change and its response to climate change in Central Asia from 1982 to 2012. *Chinese J. Plant Ecol.*, **40**, 13–23, doi:10.17521/cjpe.2015.0236. http://www.plant-ecology.com/EN/10.17521/cjpe.2015.0236.
Qian, Y., M. Huang, B. Yang, L. K. Berg, Y. Qian, M. Huang, B. Yang, and L. K. Berg, 2013: A Modeling Study of Irrigation Effects on Surface Fluxes and Land–Air–Cloud Interactions in the Southern Great Plains. *J. Hydrometeorol.*, **14**, 700–721, doi:10.1175/JHM-D-12-0134.1. http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-12-0134.1.
Rahmstorf, S., and D. Coumou, 2011: Increase of extreme events in a warming world. *Proc. Natl. Acad. Sci. U. S. A.*, **108**, 17905–17909, doi:10.1073/pnas.1101766108. http://www.ncbi.nlm.nih.gov/pubmed/22025683.
Rani, D., and M. M. Moreira, 2010: Simulation–Optimization Modeling: A Survey and Potential Application in Reservoir Systems Operation. *Water Resour. Manag.*, **24**, 1107–1138, doi:10.1007/s11269-009-9488-0. http://link.springer.com/10.1007/s11269-009-9488-0.
Renaudeau, D., J. L. Gourdine, and N. R. St-Pierre, 2011: A meta-analysis of the effects of high ambient temperature on growth performance of growing-finishing pigs. *J. Anim. Sci.*, **89**, 2220–2230, doi:10.2527/jas.2010-3329.

http://www.ncbi.nlm.nih.gov/pubmed/21297065.
Revi, A., D. E. Satterthwaite, J. Aragón-Durand, F. Corfee-Morlot, R. B. R. Kiunsi, M. Pelling, D. C. Roberts, and W. Solecki, 2014: Urban areas. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 535–612.
Rial, J. a, R. a P. Sr, M. Beniston, N. D. E. Noblet-ducoudré, and R. Prinn, Uncorrected Proof Nonlinearities , Feedbacks and Critical Thresholds Within the Earth â€™ S Climate System. 1–28.
Ricke, K. L., J. B. Moreno-Cruz, J. Schewe, A. Levermann, and K. Caldeira, 2015: Policy thresholds in mitigation. *Nat. Geosci.*, **9**, 5–6, doi:10.1038/ngeo2607. http://www.nature.com/doifinder/10.1038/ngeo2607.
RIZWAN, A. M., L. Y. C. DENNIS, and C. LIU, 2008: A review on the generation, determination and mitigation of Urban Heat Island. *J. Environ. Sci.*, **20**, 120–128, doi:10.1016/S1001-0742(08)60019-4. http://linkinghub.elsevier.com/retrieve/pii/S1001074208600194.
Rockström, J., and Coauthors, 2009: Planetary boundaries: explorint the safe operating space for humanity. *Ecol. Soc.*, **14**, 1–32, doi:10.1038/461472a.
Rockström, J., and Coauthors, 2009: Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.*, **14**, art32, doi:10.5751/ES-03180-140232. http://www.ecologyandsociety.org/vol14/iss2/art32/.
Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi, 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.*, **5**, 519–527, doi:10.1038/nclimate2572. http://www.nature.com/doifinder/10.1038/nclimate2572.
Rogelj, J., D. L. McCollum, B. C. O'Neill, and K. Riahi, 2012: 2020 emissions levels required to limit warming to below 2 °C. *Nat. Clim. Chang.*, **3**, 405–412, doi:10.1038/nclimate1758. http://www.nature.com/doifinder/10.1038/nclimate1758.
Rogelj, J., D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature*, **493**, 79–83, doi:10.1038/nature11787. http://www.nature.com/doifinder/10.1038/nature11787.
Rogelj, J., M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare, 2015: Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.*, **10**, 105007, doi:10.1088/1748-9326/10/10/105007. http://stacks.iop.org/1748-9326/10/i=10/a=105007?key=crossref.f151b273facefe80790884626a7590ad.
Root, T. L., D. P. MacMynowski, M. D. Mastrandrea, and S. H. Schneider, 2005: Human-modified temperatures induce species changes: Joint attribution. *Proc. Natl. Acad. Sci. U. S. A.*, **102**, 7465–7469, doi:10.1073/pnas.0502286102. http://www.ncbi.nlm.nih.gov/pubmed/15899975.
Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Shakal, T. Bowman, and S. Ali Ibrahim, 2015: ARC3.2 Summary for city leaders. Climate Change and Cities. Second Assessment Report of the Urban Climate Change Research Network. *Urban Clim. Chang. Res. Netw.*, 28. http://uccrn.org/files/2015/12/ARC3-2-web.pdf.
Rosenzweig, C., and Coauthors, 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3268–3273, doi:10.1073/pnas.1222463110. http://www.ncbi.nlm.nih.gov/pubmed/24344314.
Rosenzweig, C., and Coauthors, 2008: Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453**, 353–357, doi:10.1038/nature06937. http://www.nature.com/doifinder/10.1038/nature06937.
Roth, M., 2007: Review of urban climate research in (sub)tropical regions. *Int. J. Climatol.*, **27**, 1859–1873, doi:10.1002/joc.1591. http://doi.wiley.com/10.1002/joc.1591.
Sacks, W. J., B. I. Cook, N. Buenning, S. Levis, and J. H. Helkowski, 2009: Effects of global irrigation on the near-surface climate. *Clim. Dyn.*, **33**, 159–175, doi:10.1007/s00382-008-0445-z. http://link.springer.com/10.1007/s00382-008-0445-z.
Saeidi, M., F. Moradi, and M. Abdoli, 2017: Impact of drought stress on yield, photosynthesis rate, and sugar alcohols contents in wheat after anthesis in semiarid region of Iran. *http://dx.doi.org/10.1080/15324982.2016.1260073*, doi:10.1080/15324982.2016.1260073. http://www.tandfonline.com/doi/abs/10.1080/15324982.2016.1260073?journalCode=uasr20.
Salameh, T., P. Drobinski, M. Vrac, and P. Naveau, 2009: Statistical downscaling of near-surface wind over complex terrain in southern France. *Meteorol. Atmos. Phys.*, **103**, 253–265, doi:10.1007/s00703-008-0330-7. http://link.springer.com/10.1007/s00703-008-0330-7.
Santos, C. A. G., and Coauthors, 2012: Application of a simulated annealing optimization to a physically based erosion model. *Water Sci. Technol.*, **66**, 2099–2108, doi:10.2166/wst.2012.426. http://www.ncbi.nlm.nih.gov/pubmed/22949239.
Schewe, J., and Coauthors, Multimodel assessment of water scarcity under climate change. doi:10.1073/pnas.1222460110. http://www.pnas.org/content/111/9/3245.full.pdf.
Schlenker, W., and M. J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 15594–15598, doi:10.1073/pnas.0906865106.

http://www.ncbi.nlm.nih.gov/pubmed/19717432.
Schleussner, C.-F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 {&}deg;C and 2 {&}deg;C. *Earth Syst. Dyn.*, **7**, 327–351, doi:10.5194/esd-7-327-2016. http://www.earth-syst-dynam.net/7/327/2016/.
Schleussner, C.-F., and Coauthors, 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Publ. Gr.*, doi:10.1038/NCLIMATE3096. http://www.pik-potsdam.de/%7B~%7Danders/publications/schleussner%7B_%7Drogelj16.pdf.
Schmidtko, S., L. Stramma, and M. Visbeck, 2017: Decline in global oceanic oxygen content during the past five decades. *Nature*, **542**, 335–339, doi:10.1038/nature21399. http://www.nature.com/doifinder/10.1038/nature21399.
Seddon, A. W. R., M. Macias-Fauria, P. R. Long, D. Benz, and K. J. Willis, 2016: Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**, 229+, doi:10.1038/nature16986.
Seifert, C. A., and D. B. Lobell, 2015: Response of double cropping suitability to climate change in the United States. *Environ. Res. Lett.*, **10**, 24002, doi:10.1088/1748-9326/10/2/024002. http://stacks.iop.org/1748-9326/10/i=2/a=024002?key=crossref.615c30b00a05e112de05663c69ac28b7.
Semenza, J. C., S. Herbst, A. Rechenburg, J. E. Suk, C. Höser, C. Schreiber, and T. Kistemann, 2012: Climate Change Impact Assessment of Food- and Waterborne Diseases. *Crit. Rev. Environ. Sci. Technol.*, **42**, 857–890, doi:10.1080/10643389.2010.534706. http://www.ncbi.nlm.nih.gov/pubmed/24808720.
Semenza, J. C., C. Höuser, S. Herbst, A. Rechenburg, J. E. Suk, T. Frechen, and T. Kistemann, 2012: Knowledge Mapping for Climate Change and Food- and Waterborne Diseases. *Crit. Rev. Environ. Sci. Technol.*, **42**, 378–411, doi:10.1080/10643389.2010.518520. http://www.ncbi.nlm.nih.gov/pubmed/24771989.
Semenza, J. C., and B. Menne, 2009: Climate change and infectious diseases in Europe. *Lancet Infect. Dis.*, **9**, 365–375, doi:10.1016/S1473-3099(09)70104-5. http://linkinghub.elsevier.com/retrieve/pii/S1473309909701045.
Seneviratne, S. I., and Coauthors, 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA https://www.ipcc.ch/pdf/special-reports/srex/SREX-Chap3%7B_%7DFINAL.pdf.
Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling, 2010: Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Rev.*, **99**, 125–161, doi:10.1016/j.earscirev.2010.02.004. http://www.sciencedirect.com/science/article/pii/S0012825210000139.
Seneviratne, S. I., M. G. Donat, B. Mueller, and L. V Alexander, 2014: No pause in the increase of hot temperature extremes. *Nat. Clim. Chang.*, **4**, 161–163, doi:10.1038/nclimate2145. http://www.nature.com/doifinder/10.1038/nclimate2145.
Seneviratne, S. I., M. G. Donat, A. J. Pitman, R. Knutti, and R. L. Wilby, 2016: Allowable CO2 emissions based on regional and impact-related climate targets. *Nature*, **529**, 477–483, doi:10.1038/nature16542. http://www.nature.com/doifinder/10.1038/nature16542.
Seneviratne, S. I., D. Luethi, M. Litschi, and C. Schaer, 2006: Land-atmosphere coupling and climate change in Europe. *Nature*, doi:10.1038/nature05095. http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2%7B&%7DSrcAuth=ORCID%7B&%7DSrcApp=OrcidOrg%7B&%7DDestLinkType=FullRecord%7B&%7DDestApp=WOS%7B_%7DCPL%7B&%7DKeyUT=WOS:000240467000045%7B&%7DKeyUID=WOS:000240467000045.
Seneviratne, S. I., and Coauthors, 2013: Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment. *Geophys. Res. Lett.*, **40**, 5212–5217, doi:10.1002/grl.50956. http://doi.wiley.com/10.1002/grl.50956.
Serpa, D., and Coauthors, 2015: Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments. *Sci. Total Environ.*, **538**, 64–77, doi:10.1016/j.scitotenv.2015.08.033. http://www.ncbi.nlm.nih.gov/pubmed/26298249.
Serreze, M. C., and R. G. Barry, 2011: Processes and impacts of Arctic amplification: A research synthesis. *Glob. Planet. Change*, **77**, 85–96, doi:10.1016/j.gloplacha.2011.03.004. http://www.sciencedirect.com/science/article/pii/S0921818111000397.
Settele, J., and Coauthors, 2014: Terrestrial and Inland Water Systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*, C.B. Field et al., Eds., Cambridge University Press, 271–359 https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap4%7B_%7DFINAL.pdf.
Sheffield, J., E. F. Wood, and M. L. Roderick, 2012: Little change in global drought over the past 60 years. *Nature*, **491**, 435–438, doi:10.1038/nature11575. http://www.ncbi.nlm.nih.gov/pubmed/23151587.
Shufen, P., and Coauthors, 2015: Impacts of climate variability and extremes on global net primary production in the first decade of the 21st century. *J. Gepgraphical Sci.*, **25**, 1027–1044, doi:10.1007/s11442-015-1217-4.
Silva, L. C. R., and M. Anand, 2013: Probing for the influence of atmospheric CO2 and climate change on forest ecosystems across biomes. *Glob. Ecol. Biogeogr.*, **22**, 83–92, doi:10.1111/j.1466-8238.2012.00783.x.

Singh, D., M. Tsiang, B. Rajaratnam, and N. S. Diffenbaugh, 2014: Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nat. Clim. Chang.*, **4**, 456–461, doi:10.1038/nclimate2208. http://www.nature.com/doifinder/10.1038/nclimate2208.

Singh, O. P., 2010: Recent Trends in Tropical Cyclone Activity in the North Indian Ocean. *Indian Ocean Tropical Cyclones and Climate Change*, Springer Netherlands, Dordrecht, 51–54 http://www.springerlink.com/index/10.1007/978-90-481-3109-9%7B_%7D8.

Singh, O. P., T. M. Ali Khan, and M. S. Rahman, 2000: Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorol. Atmos. Phys.*, **75**, 11–20, doi:10.1007/s007030070011. http://link.springer.com/10.1007/s007030070011.

Sippel, S., J. Zscheischler, M. D. Mahecha, R. Orth, M. Reichstein, M. Vogel, and S. I. Seneviratne, 2016: Refining multi-model projections of temperature extremes by evaluation against land{&}amp;ndash;atmosphere coupling diagnostics. *Earth Syst. Dyn. Discuss.*, 1–24, doi:10.5194/esd-2016-48. http://www.earth-syst-dynam-discuss.net/esd-2016-48/.

Slot, M., and K. Kitajima, 2015: General patterns of acclimation of leaf respiration to elevated temperatures across biomes and plant types. *Oecologia*, **177**, 885–900, doi:10.1007/s00442-014-3159-4.

Smith, B., I. C. Prentice, and M. T. Sykes, 2001: Representation of vegetation dynamics in modelling of European ecosystems: comparison of two contrasting approaches within European climate space. *Glob. Ecol. Biogeogr.*, **10**, 621–637, doi:10.1046/j.1466-822X.2001.t01-1-00256.x. http://doi.wiley.com/10.1046/j.1466-822X.2001.t01-1-00256.x.

Smith, B., I. C. Prentice, and M. T. Sykes, 2008: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Glob. Ecol. Biogeogr.*, **10**, 621–637, doi:10.1046/j.1466-822X.2001.t01-1-00256.x. http://doi.wiley.com/10.1046/j.1466-822X.2001.t01-1-00256.x.

Smith, K. R., and Coauthors, 2014: Human health: Impacts, adaptation, and co-benefits. *Climate change 2014: Impacts, adaptation, and vulnerability. Part a: Global and sectoral aspects*, C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, and T.E. Bilir, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 709–754 https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap11%7B_%7DFINAL.pdf.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, and J. Minx, 2015: Smith, Biophysical and Economic limits to negative CO2 emissions. *Nat. Clim. Chang.*, **6**, 42–50, doi:10.1038/NCLIMATE2870. http://www.nature.com/doifinder/10.1038/nclimate2870.

Smith, P., and Coauthors, 2010: Competition for land. *Phil Trans R Soc*, **365**, 2941–2957, doi:10.1098/rstb.2010.0127. http://www.ncbi.nlm.nih.gov/pubmed/20713395.

Smith, P., J. Price, J. VanDerWal, A. Molotoks, R. Warren, and Y. Malhi, Impacts on terrestrial biodiversity of moving from a 2ºC to a 1.5ºC target. *in prep.*,.

Smith, R. L., C. Tebaldi, D. Nychka, and L. O. Mearns, 2009: Bayesian Modeling of Uncertainty in Ensembles of Climate Models. *J. Am. Stat. Assoc.*, **104**, 97–116, doi:10.1198/jasa.2009.0007. http://www.tandfonline.com/doi/abs/10.1198/jasa.2009.0007.

Solomon, S., and Coauthors, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.,.

Song, X., G. Zhou, Z. Xu, X. Lv, and Y. Wang, 2016: A self-photoprotection mechanism helps Stipa baicalensis adapt to future climate change. *Sci. Rep.*, **6**, 25839, doi:10.1038/srep25839. http://www.nature.com/articles/srep25839.

Sonntag, S., J. Pongratz, C. H. Reick, and H. Schmidt, 2016: Reforestation in a high-CO {<}sub{>}2{<}/sub{>} world-Higher mitigation potential than expected, lower adaptation potential than hoped for. *Geophys. Res. Lett.*, **43**, 6546–6553, doi:10.1002/2016GL068824. http://doi.wiley.com/10.1002/2016GL068824.

Stanton, E. A., F. Ackerman, and S. Kartha, 2009: Inside the integrated assessment models: Four issues in climate economics. *Clim. Dev.*, **1**, 166, doi:10.3763/cdev.2009.0015. http://www.tandfonline.com/doi/abs/10.3763/cdev.2009.0015.

Stéfanon, M., N. K. Martin-StPaul, P. Leadley, S. Bastin, A. Dell'Aquila, P. Drobinski, and C. Gallardo, 2015: Testing climate models using an impact model: what are the advantages? *Clim. Change*, **131**, 649–661, doi:10.1007/s10584-015-1412-4. http://link.springer.com/10.1007/s10584-015-1412-4.

Steffen, W., and Coauthors, 2015: Planetary boundaries: Guiding human development on a changing planet. *Science (80-.).*, **347**, 1259855, doi:10.1126/science.1259855. http://www.sciencemag.org/cgi/doi/10.1126/science.1259855.

Stegehuis, A. I., A. J. Teuling, P. Ciais, R. Vautard, and M. Jung, 2013: Future European temperature change uncertainties reduced by using land heat flux observations. *Geophys. Res. Lett.*, **40**, 2242–2245, doi:10.1002/grl.50404. http://doi.wiley.com/10.1002/grl.50404.

Sterling, S. M., A. Ducharne, and J. Polcher, 2012: The impact of global land-cover change on the terrestrial water cycle. *Nat. Clim. Chang.*, **3**, 385–390, doi:10.1038/nclimate1690. http://www.nature.com/doifinder/10.1038/nclimate1690.

Stevens, A. J., D. Clarke, and R. J. Nicholls, 2016: Trends in reported flooding in the UK: 1884–2013. *Hydrol. Sci. J.*, **61**, 50–63, doi:10.1080/02626667.2014.950581. http://www.tandfonline.com/doi/full/10.1080/02626667.2014.950581.

Stocker, T. F., 1999: Abrupt climate changes: From the past to the future - a review. *Int. J. Earth Sci.*, **88**, 365–374, doi:10.1007/s005310050271.

Stocker, T. F., and Coauthors, 2013: Technical Summary. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5%7B_%7DSummaryVolume%7B_%7DFINAL.pdf.

Stoll, S., H. J. Hendricks Franssen, R. Barthel, and W. Kinzelbach, 2011: What can we learn from long-term groundwater data to improve climate change impact studies? *Hydrol. Earth Syst. Sci.*, **15**, 3861–3875, doi:10.5194/hess-15-3861-2011. http://www.hydrol-earth-syst-sci.net/15/3861/2011/.

Stott, P. A., D. A. Stone, and M. R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610–614, doi:10.1038/nature03089. http://www.ncbi.nlm.nih.gov/pubmed/15577907.

Strauss, B. H., 2013: Rapid accumulation of committed sea-level rise from global warming. *Proc. Natl. Acad. Sci.*, **110**, 13699–13700, doi:10.1073/pnas.1312464110. http://www.pnas.org/content/110/34/13699.short.

Su, B., J. Huang, M. Gemmer, D. Jian, H. Tao, T. Jiang, and C. Zhao, 2016: Statistical downscaling of CMIP5 multi-model ensemble for projected changes of climate in the Indus River Basin. *Atmos. Res.*, **178**–**179**, 138–149, doi:10.1016/j.atmosres.2016.03.023. http://linkinghub.elsevier.com/retrieve/pii/S0169809516300850.

Sugi, M., and J. Yoshimura, 2012: Decreasing trend of tropical cyclone frequency in 228-year high-resolution AGCM simulations. *Geophys. Res. Lett.*, **39**, n/a--n/a, doi:10.1029/2012GL053360. http://doi.wiley.com/10.1029/2012GL053360.

Sui, X., and G. Zhou, 2013: Carbon dynamics of temperate grassland ecosystems in China from 1951 to 2007: an analysis with a process-based biogeochemistry model. *Environ. Earth Sci.*, **68**, 521–533, doi:10.1007/s12665-012-1756-2. http://link.springer.com/10.1007/s12665-012-1756-2.

Sun, S., X. Yang, J. Zhao, and F. Chen, 2015: The possible effects of global warming on cropping systems in China XI The variation of potential light-temperature suitable cultivation zone of winter wheat in China under climate change. *Sci. Agric. Sin.*, **48**, 1926–1941, doi:10.3864/J.ISSN.0578-1752.2015.10.006. http://www.chinaagrisci.com/EN/abstract/abstract18765.shtml.

Supit, I., C. A. van Diepen, A. J. W. de Wit, P. Kabat, B. Baruth, and F. Ludwig, 2010: Recent changes in the climatic yield potential of various crops in Europe. *Agric. Syst.*, **103**, 683–694, doi:10.1016/j.agsy.2010.08.009. http://www.sciencedirect.com/science/article/pii/S0308521X10001162.

Suzuki-Parker, A., H. Kusaka, and Y. Yamagata, 2015: Assessment of the Impact of Metropolitan-Scale Urban Planning Scenarios on the Moist Thermal Environment under Global Warming: A Study of the Tokyo Metropolitan Area Using Regional Climate Modeling. *Adv. Meteorol.*, **2015**, 1–11, doi:10.1155/2015/693754. http://www.hindawi.com/journals/amete/2015/693754/.

Sydeman, W. J., M. García-Reyes, D. S. Schoeman, R. R. Rykaczewski, S. A. Thompson, B. A. Black, and S. J. Bograd, 2014: Climate change and wind intensification in coastal upwelling ecosystems. *Science (80-.).*, **345**. http://science.sciencemag.org/content/345/6192/77.

Tang, X., and Coauthors, 2014: How is water-use efficiency of terrestrial ecosystems distributed and changing on Earth? *Sci. Rep.*, **4**, doi:10.1038/srep07483.

Tanoue, M., Y. Hirabayashi, H. Ikeuchi, E. Gakidou, and T. Oki, 2016: Global-scale river flood vulnerability in the last 50 years. *Sci. Rep.*, **6**, 36021, doi:10.1038/srep36021. http://www.nature.com/articles/srep36021.

Tebaldi, C., 2011: Mapping model agreement on future climate projections. *Geophys. Res. Lett.*, **38**, doi:10.1029/2011GL049863.

The World Bank, 2012: Turn Down the Heat: Why a 4°C Warmer World must be Avoided. *{...} Rep. World {...}*, 106. http://climatechange.worldbank.org/content/climate-change-report-warns-dramatically-warmer-world-century.

Thiery, W., E. L. Davin, D. M. Lawrence, A. L. Hirsch, M. Hauser, and S. I. Seneviratne, 2017: Present-day irrigation mitigates heat extremes. *J. Geophys. Res. Atmos.*, **122**, 1403–1422, doi:10.1002/2016JD025740. http://doi.wiley.com/10.1002/2016JD025740.

Tory, K. J., and Coauthors, 2013: Projected Changes in Late-Twenty-First-Century Tropical Cyclone Frequency in 13 Coupled Climate Models from Phase 5 of the Coupled Model Intercomparison Project. *J. Clim.*, **26**, 9946–9959, doi:10.1175/JCLI-D-13-00010.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-13-00010.1.

Trenberth, K. E., 2012: Framing the way to relate climate extremes to climate change. *Clim. Change*, **115**, doi:10.1007/s10584-012-0441-5.

Trigo, R. M., C. M. Gouveia, and D. Barriopedro, 2010: The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agric. For. Meteorol.*, **150**, 1245–1257,

doi:10.1016/j.agrformet.2010.05.006. http://linkinghub.elsevier.com/retrieve/pii/S0168192310001334.
Troccoli, A., K. Muller, P. Coppin, R. Davy, C. Russell, and A. L. Hirsch, Long-Term Wind Speed Trends over Australia. doi:10.1175/2011JCLI4198.1. http://journals.ametsoc.org/doi/pdf/10.1175/2011JCLI4198.1.
Universidade Federal da Paraíba., S., M. Moreira, and J. Corte-Real, 2014: *Journal of urban and environmental engineering*. University of Paraiba, http://periodicos.ufpb.br/index.php/juee/article/view/16453/pdf.
van der Velde, M., F. N. Tubiello, A. Vrieling, and F. Bouraoui, 2012: Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data. *Clim. Change*, **113**, 751–765, doi:10.1007/s10584-011-0368-2. http://link.springer.com/10.1007/s10584-011-0368-2.
Van Dingenen, R., F. J. Dentener, F. Raes, M. C. Krol, L. Emberson, and J. Cofala, 2009: The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmos. Environ.*, **43**, 604–618, doi:10.1016/j.atmosenv.2008.10.033. http://www.sciencedirect.com/science/article/pii/S1352231008009424.
Vautard, R., J. Cattiaux, P. Yiou, J.-N. Thépaut, and P. Ciais, 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nat. Geosci.*, **3**, 756–761, doi:10.1038/ngeo979. http://www.nature.com/doifinder/10.1038/ngeo979.
Verchot, L. V, and Coauthors, 2007: Climate change: linking adaptation and mitigation through agroforestry. *Mitig. Adapt. Strateg. Glob. Chang.*, **12**, 901–918, doi:10.1007/s11027-007-9105-6. http://link.springer.com/10.1007/s11027-007-9105-6.
Veron, J. E. N., 2008: Mass extinctions and ocean acidification: Biological constraints on geological dilemmas. *Coral Reefs*, **27**, 459–472, doi:10.1007/s00338-008-0381-8.
Vincent, L. A., X. L. Wang, E. J. Milewska, H. Wan, F. Yang, and V. Swail, 2012: A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *J. Geophys. Res. Atmos.*, **117**, n/a--n/a, doi:10.1029/2012JD017859. http://doi.wiley.com/10.1029/2012JD017859.
Vitali, A., M. Segnalini, L. Bertocchi, U. Bernabucci, A. Nardone, and N. Lacetera, 2009: Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. *J. Dairy Sci.*, **92**, 3781–3790, doi:10.3168/jds.2009-2127. http://www.ncbi.nlm.nih.gov/pubmed/19620660.
Vogel, M. M., R. Orth, F. Cheruy, S. Hagemann, R. Lorenz, B. J. J. M. van den Hurk, and S. I. Seneviratne, 2017: Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. *Geophys. Res. Lett.*, **44**, 1511–1519, doi:10.1002/2016GL071235. http://doi.wiley.com/10.1002/2016GL071235.
Vrac, M., and P. Naveau, 2007: Stochastic downscaling of precipitation: From dry events to heavy rainfalls. *Water Resour. Res.*, **43**, n/a--n/a, doi:10.1029/2006WR005308. http://doi.wiley.com/10.1029/2006WR005308.
Wada, Y., and Coauthors, 2013: Multimodel projections and uncertainties of irrigation water demand under climate change. *Geophys. Res. Lett.*, **40**, 4626–4632, doi:10.1002/grl.50686. http://doi.wiley.com/10.1002/grl.50686.
Wagner, P., and W. Kuttler, 2014: Biogenic and anthropogenic isoprene in the near-surface urban atmosphere — A case study in Essen, Germany. *Sci. Total Environ.*, **475**, 104–115, doi:10.1016/j.scitotenv.2013.12.026. http://linkinghub.elsevier.com/retrieve/pii/S0048969713014800.
Walsh, K. J. E., and Coauthors, 2016: Tropical cyclones and climate change. *Wiley Interdiscip. Rev. Clim. Chang.*, **7**, 65–89, doi:10.1002/wcc.371. http://doi.wiley.com/10.1002/wcc.371.
Walsh, K., and Coauthors, 2016: Natural hazards in Australia: storms, wind and hail. *Clim. Change*, **139**, 55–67, doi:10.1007/s10584-016-1737-7. http://link.springer.com/10.1007/s10584-016-1737-7.
Wang, D., T. C. Gouhier, B. A. Menge, and A. R. Ganguly, 2015: Intensification and spatial homogenization of coastal upwelling under climate change. *Nature*, **518**, 390–394, doi:10.1038/nature14235. http://www.ncbi.nlm.nih.gov/pubmed/25693571.
Wang, J., X. Zhang, J. Wang, and X. Zhang, 2008: Downscaling and Projection of Winter Extreme Daily Precipitation over North America. *J. Clim.*, **21**, 923–937, doi:10.1175/2007JCLI1671.1. http://journals.ametsoc.org/doi/abs/10.1175/2007JCLI1671.1.
Wang, W., J. Sardans, C. Tong, C. Wang, L. Ouyang, M. Bartrons, and J. Penuelas, 2016: Typhoon enhancement of N and P release from litter and changes in the litter N:P ratio in a subtropical tidal wetland. *Environ. Res. Lett.*, **11**, doi:10.1088/1748-9326/11/1/014003.
Warren, R., J. Price, J. VanDerWal, S. Cornelius, and H. Sohl, The implications of the United Nations Paris Agreement on Climate Change for Key Biodiversity Areas. *submitted*,.
Warren, R., and Coauthors, 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nat. Clim. Chang.*, **3**, 678–682, doi:10.1038/nclimate1887. http://www.nature.com/doifinder/10.1038/nclimate1887.
Warszawski, L., and Coauthors, 2013: A multi-model analysis of risk of ecosystem shifts under climate change. *Environ. Res. Lett.*, **8**, 44018, doi:10.1088/1748-9326/8/4/044018. http://stacks.iop.org/1748-9326/8/i=4/a=044018?key=crossref.2d722efbaf6d3e455e38f2c68888d873.
Wartenburger, R., M. Hirschi, M. G. Donat, P. Greve, A. J. Pitman, and S. I. Seneviratne, Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geosci. Model Dev. - Submitt.*,.

Weitzman, M. L., 2012: Ghg t i a c c d. **14**, 221–244.

Welch, J. R., J. R. Vincent, M. Auffhammer, P. F. Moya, A. Dobermann, and D. Dawe, 2010: Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proc. Natl. Acad. Sci. U. S. A.*, **107**, 14562–14567, doi:10.1073/pnas.1001222107. http://www.ncbi.nlm.nih.gov/pubmed/20696908.

Whiteman, G., C. Hope, and P. Wadhams, 2013: Vast costs of Arctic change. *Nature*, **499**, 401–403, doi:10.1038/499401a. http://www.ncbi.nlm.nih.gov/pubmed/23887416.

Wiens, J. J., 2016: Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLOS Biol.*, **14**, doi:10.1371/journal.pbio.2001104.

Wilhelm, M., E. L. Davin, and S. I. Seneviratne, 2015: Climate engineering of vegetated land for hot extremes mitigation: An Earth system model sensitivity study. *J. Geophys. Res. Atmos.*, **120**, 2612–2623, doi:10.1002/2014JD022293. http://doi.wiley.com/10.1002/2014JD022293.

WILSON, S. K., N. A. J. GRAHAM, M. S. PRATCHETT, G. P. JONES, and N. V. C. POLUNIN, 2006: Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Glob. Chang. Biol.*, **12**, 2220–2234, doi:10.1111/j.1365-2486.2006.01252.x. http://doi.wiley.com/10.1111/j.1365-2486.2006.01252.x.

Winsemius, H. C., and Coauthors, 2015: Global drivers of future river flood risk. *Nat. Clim. Chang.*, **6**, 381–385, doi:10.1038/nclimate2893. http://www.nature.com/doifinder/10.1038/nclimate2893.

Wolf, J., and Coauthors, 1996: Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. *Clim. Res.*, **7**, 253–270, doi:10.3354/cr007253. http://www.int-res.com/abstracts/cr/v07/n3/p253-270/.

Wouter Botzen, W. J., and J. C. J. M. van den Bergh, 2012: How sensitive is Nordhaus to Weitzman? Climate policy in DICE with an alternative damage function. *Econ. Lett.*, **117**, 372–374, doi:10.1016/j.econlet.2012.05.032. http://dx.doi.org/10.1016/j.econlet.2012.05.032.

Wu, X., R. Zurita-Milla, and M.-J. Kraak, 2016: A novel analysis of spring phenological patterns over Europe based on co-clustering. *J. Geophys. Res. Biogeosciences*, **121**, 1434–1448, doi:10.1002/2015JG003308.

Wu, X., Y. Lu, S. Zhou, L. Chen, and B. Xu, 2016: Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. *Environ. Int.*, **86**, 14–23, doi:10.1016/j.envint.2015.09.007. http://dx.doi.org/10.1016/j.envint.2015.09.007.

Xia, J., J. Chen, S. Piao, P. Ciais, Y. Luo, and S. Wan, 2014: Terrestrial carbon cycle affected by non-uniform climate warming. *Nat. Geosci.*, **7**, 173–180, doi:10.1038/NGEO2093.

Xu, Y., Z.-H. Shen, L.-X. Ying, P. Ciais, H.-Y. Liu, S. Piao, C. Wen, and Y.-X. Jiang, 2016: The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901-2013): An indicator-based approach. *Ecol. Indic.*, **63**, 258–272, doi:10.1016/j.ecolind.2015.12.023.

Yackulc, C. B., and Coauthors, 2015: To predict the niche, model colonization and extinction. *Ecology*, **96**, 16–23, doi:10.1016/S0304-3800(99)00219-7. http://www.ncbi.nlm.nih.gov/pubmed/26236885.

Yang, J., H. Tian, B. Tao, W. Ren, C. Lu, S. Pan, Y. Wang, and Y. Liu, 2015: Century-scale patterns and trends of global pyrogenic carbon emissions and fire influences on terrestrial carbon balance. *Global Biogeochem. Cycles*, **29**, 1549–1566, doi:10.1002/2015GB005160.

Yang, Z., W. Fang, X. Lu, G.-P. Sheng, D. E. Graham, L. Liang, S. D. Wullschleger, and B. Gu, 2016: Warming increases methylmercury production in an Arctic soil. *Environ. Pollut.*, **214**, 504–509, doi:10.1016/j.envpol.2016.04.069.

Yazdanpanah, M., M. Thompson, and J. Linnerooth-Bayer, 2016: Do Iranian Policy Makers Truly Understand And Dealing with the Risk of Climate Change Regarding Water Resource Management? *IDRiM*,. http://pure.iiasa.ac.at/13881/1/DoIran.pdf.

Yohe, G., K. Knee, and P. Kirshen, 2011: On the economics of coastal adaptation solutions in an uncertain world. *Clim. Change*, **106**, 71–92, doi:10.1007/s10584-010-9997-0. http://link.springer.com/10.1007/s10584-010-9997-0.

Young, I. R., S. Zieger, and A. V Babanin, 2011: Global trends in wind speed and wave height. *Science (80-.).*, **332**. http://science.sciencemag.org/content/332/6028/451.

Yunhe, Y. I. N., W. U. Shaohong, Z. Dongsheng, D. A. I. Erfu, Y. I. N. Yunhe, W. U. Shaohong, Z. Dongsheng, and D. A. I. Erfu, 2016: Ecosystem water conservation changes in response to climate change in the Source Region of the Yellow River from 1981 to 2010. *Geogr. Res.*, **35**, 49–57, doi:10.11821/DLYJ201601005. http://www.geog.com.cn/EN/abstract/abstract37200.shtml.

Yunjia, X. U., D. A. I. Junhu, W. Huanjiong, L. I. U. Yachen, X. U. Yunjia, D. A. I. Junhu, W. Huanjiong, and L. I. U. Yachen, 2015: Variations of main phenophases of natural calendar and analysis of responses to climate change in Harbin in 1985-2012. *Geogr. Res.*, **34**, 1662–1674, doi:10.11821/DLYJ201509005. http://www.progressingeography.com/EN/abstract/abstract36750.shtml.

Zacharias, S., C. Koppe, and H.-G. Mücke, 2014: Influence of Heat Waves on Ischemic Heart Diseases in Germany. *Climate*, **2**, 133–152, doi:10.3390/cli2030133. http://www.mdpi.com/2225-1154/2/3/133/.

Zacharias, S., C. Koppe, and H.-G. Mücke, 2014: Climate Change Effects on Heat Waves and Future Heat Wave-Associated IHD Mortality in Germany. *Climate*, **3**, 100–117, doi:10.3390/cli3010100.

http://www.mdpi.com/2225-1154/3/1/100/.
Zang, Q., X.-L. Yuan, X. Chen, G.-P. Luo, and L.-H. Li, 2016: Vegetation dynamics and its response to climate change in Central Asia. *Chinese J. Plant Ecol.*, 13–23, doi:10.17521/cjpe.2015.0236. http://www.plant-ecology.com/EN/10.17521/cjpe.2015.0236.
Zhang, K., R. Wang, H. Wang, H. Zhao, Y. Qi, F. Zhao, and L. J, 2016: Effects of simulated warming on dry matter production and distribution of rainfed spring wheat in semi-arid area. *Trans. Chinese Soc. Agric. Eng.*, **32**, 223–232.
Zhang, Q., X.-L. Yuan, X. Chen, G.-P. Luo, and L.-H. Li, 2016: Vegetation dynamics and its response to climate change in Central Asia. *Chinese J. Plant Ecol.*, **40**, 13–23, doi:10.1007/s40333-016-0043-6. http://www.plant-ecology.com/EN/10.17521/cjpe.2015.0236.
Zhang, R., C. A. G. Santos, M. Moreira, P. K. M. M. Freire, and J. Corte-Real, 2013: Automatic Calibration of the SHETRAN Hydrological Modelling System Using MSCE. *Water Resour. Manag.*, **27**, 4053–4068, doi:10.1007/s11269-013-0395-z. http://link.springer.com/10.1007/s11269-013-0395-z.
Zhao, L., X. Lee, R. B. Smith, and K. Oleson, 2014: Strong contributions of local background climate to urban heat islands. *Nature*, **511**, 216–219, doi:10.1038/nature13462. http://www.nature.com/doifinder/10.1038/nature13462.
Zheng, C. W., J. Pan, and C. Y. Li, 2016: Global oceanic wind speed trends. *Ocean {&} Coast. Manag.*, **129**, 15–24, doi:10.1016/j.ocecoaman.2016.05.001. http://www.sciencedirect.com/science/article/pii/S0964569116300850.
Zhou, D., S. Zhao, S. Liu, L. Zhang, and C. Zhu, 2014: Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sens. Environ.*, **152**, 51–61, doi:10.1016/j.rse.2014.05.017. http://www.sciencedirect.com/science/article/pii/S0034425714002053.
Zhu, Z., and Coauthors, 2016: Greening of the Earth and its drivers. *Nat. Clim. Chang.*, **6**, 791+, doi:10.1038/NCLIMATE3004.
Zickfeld, K., and T. Bruckner, 2003: Reducing the risk of abrupt climate change: emissions corridors preserving the Atlantic Thermohaline Circulation. *Integr. Assess.*, **4**, 106–115, doi:10.1076/iaij.4.2.106.16702. http://dx.doi.org/10.1076/iaij.4.2.106.16702%7B%25%7D5Cnhttp://www.tandfonline.com/doi/abs/10.1076/iaij.4.2.106.16702%7B#%7D.VMe1Ky4bgak.
Zickfeld, K., T. Slawig, and S. Rahmstorf, 2004: A low-order model for the response of the Atlantic thermohaline circulation to climate change. *Ocean Dyn.*, **54**, 8–26, doi:10.1007/s10236-003-0054-7.
Academic paper (PDF): Assessment of the Impact of Metropolitan-Scale Urban Planning Scenarios on the Moist Thermal Environment under Global Warming: A Study of the Tokyo Metropolitan Area Using Regional Climate Modeling. https://www.researchgate.net/publication/279231516%7B_%7DAssessment%7B_%7Dof%7B_%7Dthe%7B_%7DImpact%7B_%7Dof%7B_%7DMetropolitan-Scale%7B_%7DUrban%7B_%7DPlanning%7B_%7DScenarios%7B_%7Don%7B_%7Dthe%7B_%7DMoist%7B_%7DThermal%7B_%7DEnvironment%7B_%7Dunder%7B_%7DGlobal%7B_%7DWarming%7B_%7DA%7B_%7DStudy%7B_%7Dof%7B_%7Dthe%7B_%7DTokyo%7B_%7DMetropolitan%7B_%7DArea%7B_%7DUsing%7B_%7DRegional%7B_%7DClimate%7B_%7DModeling (Accessed April 12, 2017).

Chapter 4: Strengthening and implementing the global response

Coordinating Lead Authors: Heleen de Coninck (Netherlands) and Aromar Revi (India)

Lead Authors: Mustafa Babiker (Sudan), Paolo Bertoldi (Italy), Marcos Buckeridge (Brazil), Anton Cartwright (South Africa), Wenjie Dong (China), James Ford (Canada), Sabine Fuss (Germany), Jean-Charles Hourcade (France), Debora Ley (Guatemala/Mexico), Peter Newman (Australia), Seth Schultz (USA), Linda Steg (Netherlands), Taishi Sugiyama (Japan), Anastasia Revokatova (Russian Federation)

Contributing Authors: Fernando Aragon-Durand (Mexico), Amir Bazaz (India), Sari Kovats (UK), Elmar Kriegler (Germany), Luis Mundaca (Sweden/Chile), Maria Virginia Vilarino (Argentina), Bronwyn Hayward (New Zealand), Penny Urquhart (South Africa), Arjan van Rooij (Netherlands)

Review Editors: Rizaldi Boer (Indonesia), Diana Urge Vorsatz (Hungary)

Date of Draft: 14 avril 2017

Executive Summary

4.1 Introduction

This chapter outlines possibilities of how to strengthen and implement the global and regional responses to limit future temperature increases to 1.5 °C above pre-industrial levels over the near-term (present to 2030s), medium-term (2030-50s) and long term (2070s-2100), consistent with a variety of mitigation, adaptation and sustainable development pathways.

4.1.1 The Anthropocene & AR5 as a starting point

Anthropogenic processes now rival natural forces as drivers of the state of the Earth system (Waters, 2016; Steffen, 2007). Climate change is one such example; GHG concentrations and average surface temperatures are increasing at a rate estimated at two orders of magnitude greater than the Holocene baseline rate. This has led some scholars to claim that a new geological era of the Anthropocene has taken hold (Gaffney and Steffen 2017; Schellnhuber 1998).

Building on this, the IPCC AR5 provides a point of departure for this chapter, which, when read along with the Paris Agreement, provides a context to the challenge of strengthening the implementation of a 1.5 °C goal. The following section summarises key findings of AR5 and links them to the aims of this chapter.

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented over the last 0.8 million years. In recent decades, changes in climate have caused widespread impacts on natural and human systems on all continents and across the oceans (IPCC 2014; UNFCCC 2015a). Surface temperatures are projected to rise over the 21st century under all assessed emission scenarios, propelling the global commitment to strengthen the global and regional climate responses to limit warming to well below 2 °C and making efforts to keep warming below 1.5 °C (UNFCCC 2015a).

Chapter 2 of this report indicates that limiting climate change risks, within the context of sustainable development, will require substantial and sustained reductions in greenhouse gas emissions, and Chapter 3 indicates that this needs to go hand in hand with wide-ranging adaptation actions. The IPCC AR5 Synthesis Report already outlined multiple mitigation pathways that are likely to limit warming to below 2 °C relative to pre-industrial levels (Pachauri et al. 2014). 1.5 °C pathways would require more substantial emissions reductions over the next few decades, and most would require below-zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century.

Implementing reductions to contain warming below 2 °C poses substantial technological, economic, social and institutional challenges, which will increase if delays persist in near-term mitigation and if key technologies (e.g. CCS) are not available or economically unviable (Pachauri et al. 2014). Limiting warming to 1.5 °C involves deeper challenges on an accelerated timescale, which implies front-loaded investments (scrapping) and mitigation actions, addressing multiple policy and implementation challenges such as making carbon pricing effective; stranded assets and carbon lock-in associated with infrastructure; local, regional and global climate governance and spill-over effects.

All of these would require rapid strengthening of governance, institutional capacities, financing, innovation and behavioural change at a previously unprecedented scale (Pachauri et al. 2014; Termeer et al. 2017). It would also need new partnerships with citizens, communities, enterprises and local and regional governments that form the basis of the 2030 Development Agenda (UN, 2015, UN Habitat, 2016).

Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation and contribute to climate-resilient pathways for sustainable development (see Section 5.5.2.2). Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change (Pachauri et al. 2014). Limits to adaptation may be reached during transient and medium-range overshoot of the 1.5 °C goal.

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national. Policies across all scales supporting technology development, diffusion and transfer, as well as finance for responses to climate change, can complement and enhance the effectiveness of policies that directly promote adaptation and mitigation. (AR5, SYR)

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods and behavioural and lifestyle choices (AR5, SYR). Especially regions, hot-spots and systems at risk, that are expected to bear the brunt of short- and medium-run climate impacts, joined-up mitigation and adaptation actions, could build on these common enabling factors and potential implementation synergies. Pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels would require even earlier changes at higher rates and degrees of transformation (IPCC 2016).

4.1.2 Framing systems: ecological, social, economic, innovation

The framing of implementation arrangements to enable 1.5 °C-related transformations, in this chapter, draws upon the United Nations 2030 Sustainable Development agenda that has a climate goal in SDG 13 (United Nations 2015), and the Paris Agreement (UNFCCC 2015a). This is articulated around three interlinked systems: the ecological, the economic and social and their systemic interaction with the climate system to deliver viable climate-resilient development pathways.

The goal of the Paris Agreement of staying well below a 2 °C temperature rise, or below 1.5 °C, has, in the Agreement text, been translated to peaking of GHG emissions in the short-term and balancing GHG emissions and sinks in the second half of the 21st century. This realistically cannot be achieved using climate mitigation policy alone, and expands the scope of this assessment to disruptive technological and social innovation as well as financial and behavioural change that will enable the 'bending of the curve' by the 2030s to avoid dangerous climate change and the risk of overshoot beyond 1.5 °C (UNFCCC 2015a).

Chapter 4 therefore assesses whether combined and coordinated cross-sectoral and cross-actor action around mitigation and adaptation (as suggested in AR5) and in extremis net negative-emission CDR and SRM

(AR5, SYR) could make up a suite of development pathways to meet the regional and global goals on containing temperature rise to 1.5 °C, along with a set of other linked and critical variables, like precipitation and later in the century, sea level rise.

4.1.3 Global context and dynamics

The global context since the turn of the century is an increasingly interconnected world, with a human population growing from a current 7+ billion to over 9 billion by mid-century (United Nations 2015), consistent growth of global economic output, wealth and trade; along with a significant reduction in extreme poverty, in spite of local and regional economic crises; rising inequality, exclusion and social stratification in many regions, trends that could continue for the next few decades (Burt et al. 2014).

The expansion of urbanisation across most geographies, including more recently East and South Asia and Africa, had dramatic impacts on economic growth, productivity, employment potential and the demand for and use of fossil fuels, to meet rapidly growing energy and consumption demand, in the face of regional energy poverty, reducing food and water security in some regions; reducing biodiversity and increasing environmental conflict (World Bank 2015). This in turn has a moderate to severe impact on the lives and livelihoods of large numbers of poor and vulnerable people, especially those living in climate hot-spots (World Bank 2016).

In short, the dynamics of the climate system and its feedback on social, economic and ecological are closely tied to emerging demographic, consumption, economic and technological trends.

4.1.4 Global response: Paris Agreement

By 2015 most countries agreed to follow several international commitments associated with sustainable development. These include the Sendai Framework on Disaster Risk Reduction, the Addis Ababa Action Agenda for Financing for Development, Agenda 2030 and the Sustainable Development Goals and the Paris Agreement on Climate Change. The COP21 Paris Agreement seeks to strengthen the global response to the threat of climate change, limiting the increase of global average temperature to "well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels", with the “aim to reach global peaking of greenhouse gas emissions as soon as possible” and “achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century” (UNFCCC 2015a).

The earlier UNFCCC Structured Expert Dialogue (UNFCCC 2015c) concluded that limiting global warming to below 2 °C necessitates a radical transition through deep decarbonization starting immediately, not merely a fine tuning of current trends (IPCC 2016).

Following several unsuccessful attempts at building party confidence and consensus, COP21 was negotiated based on bottom-up, voluntary Nationally Determined Contributions (NDCs). The NDCs will be evaluated and, if needed, ratcheted up every 5 years through a global stocktaking mechanism established by the UNFCCC, supported by a facilitative dialogue in 2018, and a first formal review in 2023. This forms the first element of the implementation of the international institutional scaffolding for addressing emerging climate challenges.

A new component of the Paris Agreement was “the embrace of climate action by sub- and non-state actors” (Hale 2016). Nevertheless, current NDCs, even in combination with non-state action, will be insufficient to reach the temperature goals of the Paris Agreement, especially the 1.5 °C target (Peters et al. 2017; Fawcett et al. 2015; Roelfsema et al. 2015).

4.1.5 Reading guide and place in this Special Report

This chapter builds on the framing provided by Chapter 1, emission and mitigation pathways defined by Chapter 2, and an assessment of climate impacts and adaptation pathways presented in Chapter 3. In section

4.2, we sketch what 1.5 °C worlds might look like, both from a mitigation perspective and from an impacts and adaptation perspective. Section 4.3 discusses pathways to 1.5 °C in a generic way, and section 4.4 assesses the implications of 1.5 °C pathways for different sectors and geographic and institutional scales. Section 4.5 then discusses the enablers of implementation of 1.5 °C pathways, and how they can be strengthened. This then provides the basis for the assessment of the contribution of 1.5 °C goals to climate-resilient development pathways, poverty and inequality reduction in Chapter 5.

4.2 Visions of 1.5 °C worlds

What do 1.5 °C worlds look like? The goal of limiting the average world temperature increase to 1.5 °C above pre-industrial levels will involve the coordination of significant actions. It will be necessary to design careful development of strategies, policies and activities, including means of implementation and evaluation.

At the same time, a 1.5 °C world has not yet been defined and goes beyond limiting greenhouse gas emissions. Both the attainment, and the stability, of a 1.5 °C world depends on the achievement of the different sustainable development goals, including of poverty reduction, and keeping in mind the principles of equality and inclusion, to name but a few, and building-up adaptive capacity including reducing vulnerability to extreme weather events.

This section will look at different 1.5 °C worlds starting with an analysis of combinations of different Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) that, when modelled, for instance using Integrated Assessment Models (IAMs), would be consistent with 1.5 °C worlds. This section also analyzes the state of sustainable development and different transformations taking place that shape environmental, economic, and social systems and their integration.

4.2.1 Temporal and spatial envelopes and dynamics of 1.5 °C worlds

RCP scenarios as defined in AR5 provide a guide to assembling a set of possible visions of the world as it reaches 1.5 °C. These scenarios identify temporal envelopes of when (or if) the world will limit temperature rise to 1.5 °C. Studies assessed in AR5 also try to foresee regional impacts. However, whether or not such scenarios will be reached depends on several human-related factors. Those in turn depend on, amongst other things, policies adopted at different levels (communities, organizations, cities, states, provinces and countries).

Thus, the maintenance of the world average temperature around 1.5 °C will be dependent on elements such as interactions of policies and actions at different levels of organization and different temporal scales. Although for the first time there is attention to non-state action, the Paris Agreement (UNFCCC 2015a) still primarily relies on country actions as the organizational level that would control the pace of climate change. These actions, however, are increasingly local policies derived from actions adopted by communities, cities and other larger organization levels in each country.

On the other hand, the dynamics of the Human System (HS), including the biosphere and atmosphere, is very complex and requires inter-, trans- and multidisciplinary cooperation (Geels et al. 2016). As an adaptive complex system, the dynamics of the HS could transition to different points of equilibrium in the multidimensional space of possibilities, depending on the policies adopted and the ensuing pathways.

Using the SSPs frameworks and coupled models focused on the uses of energy and land, on population and on greenhouse gas emissions, and treating the HS as a dynamic adaptive complex system, this section will try to envisage possible temporal and spatial envelopes needed to avoid the world to cross the barrier of 1.5 °C by 2030.

4.2.1.1 A selection of the SSPs

This section will discuss the concept of Shared Socioeconomic Pathways (SSP) and their association with quantitative modelling. The Shared Socioeconomic Pathways (SSPs) have been developed as a conceptual framework in the last five years (O'Neill et al. 2017). SSPs describe a group of alternative pathways of future societal development. They consist of five narratives of futures that are driven by different socioeconomic combinations. Chapter 2 discusses the SSPs at more length.

SSP narratives have been combined with IAMs to produce quantitative views of the future up to 2100 (reviewed by Riahi et al. (2015)) using energy, land use, population and greenhouse gas emissions. SSPs seem to function as one of the means to produce tentative visions of the world at 1.5 °C on the basis of regional and global efforts to adopt or not more sustainable pathways.

In this section, we explain how SSPs and coupled modelling frameworks can be used to build visions of the world at 1.5 °C warming. SSPs are not "routes to be adopted", but descriptions of possible scenarios. Based on those descriptors, the world at 2017 can be pictured as in SSP2. This is so because at this moment there are both measures being taken towards sustainable pathways that comply with increasing mitigation (e.g. development of renewable energy technologies) and that characterize SSP1, along with measures that have been described as narratives of the SSPs 3 to 5 (e.g. adoption national policies as opposed to global ones, return to the use of fossil fuels).

To picture possible visions of the world at 1.5 °C, in this chapter we will assume – following model outcomes discussed in AR5 - that this situation would be reached around 2030.

When modelled with IAMs, SSPs narratives are often rolled out to 2100. But in many of the cases modelled (population & education, urbanization, GDP, energy demand), it is already possible now to distinguish among the 5 SSPs. Therefore, if SSP narratives and the coupled modelling system are correct, the visions of the world at 1.5 °C would work as a signal to what could be expected by mid-century. This is so, because the adoption of measures that set the world either on a sustainable (SSP1-2) or in a politically complex/fossil fuel (SSP3-5) tracks will have certain inertia that will make possible transitions more difficult and slower.

In this chapter, we will adopt two main SSP clusters: SSP1-2, associated with a more sustainable pathway which allows 1.5 °C to remain within reach with relatively limited efforts, and SSP3-5, consistent with national rivalry, higher inequality and higher use of fossil fuels, and that would require more drastic measures to limit temperature rise to 1.5 °C.

SSPs provide a useful high-level description of the relationships between policy, population and anthropogenic warming. Recent efforts have added the age, gender and educational attainment to the demographic models that inform SSPs (Samir and Lutz 2014) and included urbanisation rates as a determinant of consumption and emissions (Jiang and O'Neill 2017). IAMs and SSPs are unable to incorporate qualitative information regarding social, technological and economic processes relevant to 1.5 °C worlds (Geels et al. 2016). An example is the doubling of Africa's urban population over the next two and a half decades from 470 million people in 2015, which is taking place at much lower income levels than urbanisation in other regions (Freire et al. 2014) Lall, Henderson, & Venables, n.d.; Spence, Clarke, & Robert, 2009), and thus appears to not be driving an energy and carbon-intensive industrialisation phase of economic expansion (OECD, 2016). This type of qualitative insight is crucial in identifying the possible pathways to a global economy that has zero net emissions, which is needed in the second half of this century to avoid the "severe, widespread and irreversible impacts" (IPCC 2014).

Once greenhouse gas emissions are viewed as the by-product of social and economic systems, climate becomes endogenous to the economic and social system under analysis (Geels et al. 2016; Daron et al. 2015). This leads to new and important insights into mitigation pathways (Daron et al., 2014), including the potential for more dynamic and ambitious changes than is sometimes portrayed in SSPs.

4.2.1.2 Other modelling frameworks and visions

The idea that climate and economic systems are linked, and in addition involve other systems such as socio-technical, socio-cultural and political systems, introduces the notion of socio-ecological systems (SES), and creates the potential for more rapid and profound change that could, in itself, be useful in pursuing ambitious climate targets (Berkhout 2002). As Lambin (2005) points out, "Coupled socio-ecological systems (SES) grow, adapt, transform and collapse, at different scales – the stages of adaptation and collapse are not viewed as alternative routes but rather as part of a cycle that is driven by fast and slow, small and big events that can cascade up the scales."

4.2.1.2.1 Visions of a different socio-technical system

Similarly, when connected with sector-based socio-technical systems, the potential for "radical innovations" emerges and new futures emerge as a possibility (Geels 2004). It can also elucidate the important interactions ("networks") between "actors", "rules" (or institutions) and technology, and the importance of aligning these at different scales, in order to affect transformative change (Geels 2004; Bergek et al. 2008). The rapid uptake of photovoltaic technologies, for example, is driven by economic incentives, behavioural changes and policies in different parts of the world and as a result exceeds projections in many economic models and models of conventional technology assimilation (Geels et al. 2016; Newman 2017).

4.2.1.2.2 Visions of sustainable development and adaptation

AR5 (Section 3.3) recognises this potential when it states with a "high" degree of confidence that transformations in economic, social, technological and political decisions and actions can enhance adaptation and promote sustainable development. Furthermore, where adaptation and mitigation are restricted to incremental changes to systems and structures, without considering transformational change, this may increase the cost and losses of the required change and forego important synergies in change. Adaptation pathways are enhanced by iterative learning, deliberative processes and innovation.

4.2.1.2.3 Visions of sustainable lifestyles

Sustainable lifestyles can also have a significant impact on emissions pathways. This section will assess the literature around outcomes for sustainable lifestyles, including the economy of sufficiency. As an example, the Sustainable Lifestyles 2050 project, commissioned by the European Commission, studies ways for lifestyle patterns to evolve and how this can both overcome a harmful environment and help guide a less carbon-intensive lifestyle pathway. This project indicatively defined sustainable lifestyles as comprising travel of no more than xxxx km year^{-1}, energy use and appliances use limited to xx, consumption capped at a certain level, and living floor space also limited.

4.2.1.2.4 Visions of 1.5 °C worlds with Solar Radiation Management

Scenarios that use mitigation would not remain below 1.5 °C could remain below if Solar Radiation Management (SRM) would be applied. These pathways include, for example, SSP4, SSP5, RCP6.0, RCP8.5 and situations with failed mitigation. In these cases, SRM must only supplement ambitious emissions reductions. SRM options (see AR5 SYR Box 3.3 and Section 4.3.4 of this report for a brief review) could offset at least part of human-caused radiative forcing and keep global mean temperature below 1.5 °C (Tilmes et al. 2016; Kravitz et al. 2016; Latham et al. 2014; Ekholm and Korhonen 2016), such as when 1.5 °C comes in sight, when the rate of warming needs to be mitigated, for temporary "peak-shaving" in temperature overshoot situations and when local impacts of 1.5 °C or more are particularly severe (Ryaboshapko 2015). However, it is also likely that SRM deployment can lead to severe side effects (described in Chapter 3 and Section 4.3.4), that are partly unpredictable.

4.2.1.2.5 Visions of 1.5 °C worlds with Carbon Dioxide Removal

As well as SRM there are geo-engineering approaches that can remediate the atmosphere by carbon dioxide removal or CDR. The IPCC expressed concern at the risks involved in large scale rapid decarbonization through CDR involving terrestrial or ocean engineering (IPCC AR5, 2014). A response has been to suggest urban geoengineering using the technology and economic strengths of cities to extract carbon from the atmosphere (Thomson and Newman 2016; Fink 2013). This would use a combination of technologies such as '3rd way' technologies suggested by (Flannery 2015) as well others outlined in Box Y.1.

Cities are also able to integrate the SDG's into their spatial and infrastructure policies to enable inclusive, safe, resilient and sustainable outcomes that are also enabling the 1.5 °C limit.

[START BOX 4.1 HERE]

Box 4.1: CDR and urban geoengineering

Urban geoengineering, in combination with renewable energy in a low demand and highly efficient urban environment, can turn cities into CDR machines, while at the same time reducing emissions at source. A range of novel techniques can be applied to urban geoengineering including:

1. Carbon-negative construction such as:
    - Carbon absorbing cement that takes CO_2 from industrial waste and incorporates it into cement and carbon negative plastics that capture CO_2 from the air.
    - "Energy Plus" buildings that generate more electricity than they consume thus offsetting other high carbon energy sources.
    - Prefabricated low carbon housing from biogenic materials (e.g., cross laminated timber, straw composite) that effectively sequester carbon if the biogenic materials are harvested from plantation sources.
2. Carbon negative landscaping using serpentine rocks that, when crushed, absorb CO_2 from the air;
3. Carbon negative waste streams, such as biochar from combustible timber waste (e.g., from sources such as biogenic building material offcuts, forestry and agricultural waste);
4. Carbon negative industrial products, such as the industrial manufacturing of carbon nanofibers for many functions and carbon fibre replacing steel;
5. Urban and bioregional forestry and biophilic urbanism to absorb carbon biomass.

Sources: see below

[END BOX 4.1 HERE]

[START BOX 4.2 HERE]

Box 4.2: Complex systems and wicked problems

This box will describe the concept of Adaptive Complex Systems, highlighting the idea that the Human System is one of them. The focus is to show to the reader that depending on how subsystems interact, different emergent properties may become largely distinct outputs. The content of this box is to provide concepts that will be used by the reader through all the chapters so that the vision of the whole system behaviour as a result of different routes could be appreciated in the context of the 1.5 °C.

[END BOX Y.2 HERE]

4.2.1.3 Uncertainties

Innate uncertainty has to feature as a part of these visions for 1.5 °C worlds, as well as those identified by SSPs. Ambitious climate targets will draw on a combination of international and local action. Pielke (2013) notes that Regional Climate Downscales (RCD) often do not lead to improved skill in regional climate projections. Indeed, all climate models, irrespective of their resolution, suffer from reliability issues owing to inherent model inadequacies, imperfect understanding of key system processes, the inability to thoroughly sample model uncertainties and a lack of adequate initialisation (Stainforth et al. 2007). Any RCD "forecast" will not only be model-, method- and scenario-specific but also conditional on irreducible aleatory uncertainties (Lorenz 1976; Pielke and Zeng 1994; Rial et al. 2004; Daron and Stainforth 2013). Planning for this uncertainty places a premium on retaining the ability to respond to a wide range of difficult to predict contingencies (Low et al., 2003; Hallegatte, 2008).

4.2.2 State of sustainable development and transformations

This section will discuss the SDGs, especially their link to climate change (including but going beyond SDG13), as well as sustainable development beyond the SDG's, and going beyond 2030. SDGs will be discussed in the context of the SSPs, so that the possible transitions will be highlighted. Transition research has developed in the last decades to analyse the co-dynamics of technological, institutional, social and economic elements in the provision of key functions such as energy, water and food supply (Halbe 2017).

Within this discussion, we will emphasize the importance of equity, justice and poverty alleviation in the different visions of a 1.5 °C world.

We describe the technological transformations taking place and their possible (positive or negative) impacts on environmental, economic, and social systems; keeping in mind that infrastructure (and maybe add the word 'technology') of today will potentially last beyond 2030. What are the implications of this?

The SDGs are put into the context of the SSPs, highlighting the connections between them to give a picture of the whole systems behaviour.

4.2.2.1 Environmental systems

Healthy environmental systems are essential for a 1.5 °C sustainable world, and, together with robust adaptation strategies, will help achieve diverse sustainable development goals. Environmental systems provide the support on which other systems function, for example, through the use of ecosystem and environmental services and natural resources, which provide goods and services for economic sectors; and strategies such as integrated watershed management, which ensure water availability for agriculture and human consumption.

We provide an analysis of what environmental systems need to look like in a 1.5 °C world to meet the needs and livelihoods of growing populations while reducing or avoiding GHG emissions. This includes food production, water production and electricity generation. While the use of bioenergy may provide competition for food production, it is not always the case, and the use of other renewable energy sources, primarily hydroelectric energy, depend on watershed management.

- Forestry, REDD+, LULUCF/AFOLU: The reduction of deforestation is key to the maintenance of 1.5 °C. Forests around the world not only capture carbon, but also participate in the equilibrium of the water cycle in the atmosphere. Forests, such as the Amazon for instance, participate strongly in the equilibrium of the whole planet. Although the pace of deforestation has decreased during the last decades, burning is still occurring and needs to be suppressed to zero in a 1.5°C world. More than that, reforestation should be seriously considered as a target in order to increase mitigation under SSP1 or adaptations in cases more associated to the other SSPs.
- What do environmental systems provide to populations and what populations can provide back to environmental systems
  - The pace of the actual temperature elevation and the impacts foreseen by AR5 are consistent with unprecedented species extinction. The decay in forests (the increase in tree mortality and phenology changes due to elevation of CO_2, decrease in water and increase in temperature) may disconnect ecological relation and produce negative loops that will lead to mass extinction in the future.
  - Likewise, the sea is a giant controller of the biosphere, being responsible for many interconnections that maintain the climate in equilibrium. Scenarios like SSP5, in which mitigation is abandoned and elevation of CO_2 is foreseen to be very high, have a strong potential to lead sea pH to a forward loop that will provoke exponential increase in CO_2 concentration and accelerate drastically the effects of the climate change. This situation will require the development of technologies that could cope with enormous atmospheric changes and in such case the only possibility will be the use of Geoengineering.
- Concepts such as life-cycle assessment and holistic approaches: Considering the biosphere as a complex network, any measures taken up to 2030 have the potential to “lock” the Human System into specific SSPs or intermediate SSP situations for a certain time. Most life-cycles are quite robust on Earth, but possible “butterfly effects” could exist. Thus, potential weaknesses of the life cycles seen as a whole Adaptive Complex System should be examined.
- Bioenergy and agriculture: Bioenergy (mostly bioethanol and biodiesel) are a must in SSP1, but also play a key role in the other SSPs. The biomass conversion technologies (agro and industrial) are developing very quickly and opening new markets in a very high pace. They will become an important factor in any route taken. Although in certain regions there might be a clash between food and fuel production, in most cases (e.g. Brazil and Africa) for a 2030 scenario the available land can afford fuel production without

affecting food production. Other renewable types of energy (e.g. wind and photovoltaic) are likely to rise quickly in the next two decades, while liquid fuels can complement the plethora of renewables in order to meet SSP1 for instance.

- Link of environmental systems to poverty alleviation: Hallegatte and Mach (2016) urge climate change efforts to be better aligned to local economic development priorities (not sure if we should discuss this here). There are two main aspects related to poverty and environment. One is the fact that under some SSPs (3 to 5), adaptation challenges are high due to inequality, meaning that poor populations will become progressively more vulnerable to the impacts of Climate Change. Alternatively, this problem is consistently addressed in SSPs 1 and 2. The other aspect is that in many regions where environmental systems are being affected by forest degradation, the decay in ecosystems services ranging from the sustainable use of biodiversity locally to the changes in climate provoked by climate teleconnections would probably put poor populations in danger. This is critical for SSPs 3 to 5.
- Managing the trade-offs between increasing biofuel production and the negative climate and ecological consequences of growing and processing bioenergy crops is possible, but requires a location specific strategy (Jonker et al. 2017).

4.2.2.2 Economic systems

Recognising the origins of anthropogenic global warming in economic activity, places the focus of efforts to limit warming to 1.5 °C on the nature of this activity and economic reforms. These reforms have the potential to yield multiple benefits. The Global Commission on the Economy and Climate (GCEC) confirmed that the transitions required to meet ambitious mitigation targets are capable, of not only delivering improved living standards and sustained economic growth, but also of saving money relative to more greenhouse gas intensive development pathways (Global Commission on the Economy and Climate (GCEC) 2014).

Central to this outcome is the idea that economic growth and gains in wellbeing can be decoupled from resource consumption and greenhouse gas emissions. The idea of “a-growth”, as opposed to sustainable de-growth or growth, focuses on the policies and transactions that could drive the global economy while remaining within environmental limits (e.g. Van den Bergh 2011).

The documented examples indicating how this might be achieved are few and far between and many economic leaders remain apprehensive (Resnick et al. 2012). Macro-economic models that include ecological limits, suggest that all countries need to become much more efficient at transforming natural resources into human well-being if the Earth’s population is to live both well and sustainably (Hallegatte 2015; O’Neill 2015). This finding places the emphasis on the evidence for new economic development pathways.

4.2.2.3 Social systems

This section analyzes the implications of institutions, governance structures and policies for the implementation of transformation pathways leading to meeting the SDG's and going beyond 2030. Social systems in a 1.5 °C world will need strengthened governance and better integrated and streamlined institutions and policies at all scales from national to sub-national actors, and including non-state actors. Strengthened social systems will also consider behaviour, values, ethics, cultural and religious concerns, considering the diverse populations of urban, peri-urban, rural and indigenous populations in their different landscapes.

How social systems behave and interact will be key determinants of pathways adopted locally. These local decisions are thought to influence the levels of organization above the local, thus determining national and supranational decisions (Geels et al. 2016). Thus, the social interconnections will play an important role in the humanity being or not within the envelopes of the SSP narratives.

Behavioural and lifestyle changes are needed to realize a 1.5 °C world, but such changes should not seriously threaten quality of life. Hence, it is important to understand how engagement in different adaptation and mitigation actions affects quality of life. We will introduce a broad conception of quality of life, including hedonic as well as eudemonic dimensions: life should be pleasurable, but also and particularly meaningful.

There is literature that links communities with strong governance structures to better adaptation and sustainable development results, check how this can be scaled up as strong governance needs to happen at all scales to achieve a 1.5 °C world, both for transformation to SD, but also for climate change adaptation.

4.2.2.4 Integrated systems for 1.5 °C worlds

This section will contain brief reminders of concepts such as systemic transformation, differentiation, inclusion, equity (Chapter 5). A 1.5 °C world may require a systemic transformation of the environmental, economic and social systems as well as a transformation in the way they interact. This will depend on the routes chosen as a result of the adopted (or not) INDCs as connected with the SSPs. The SDGs call for equity and inclusion of all, which will be seen across environmental, economic, and social systems and throughout their integration. In SSP-terms, this implies that only routes around SSP1-2 can envision worlds with temperature rises below 1.5 °C. Alternatively, if the route that fits in SSP3-5 prevails, it becomes more likely that SRM and CDR technologies will have to be used for remaining below 1.5 °C, increasing the risk for human systems. However, as indicated, if other frameworks, lifestyles, cultural attitudes, transitions and systemic changes would phase in, the solution space might look differently.

This assessment will be done systemically. We will take into account scales from individuals and firms to government actors to international organisations, and will include discussion of off-sets, trade-offs, co-benefits and negative impacts between systems, how to maximize trade-offs and co-benefits and minimize negative impacts or one system over another. We will try to show which likely emergent properties would prevail by 2030 under different SSPs clusters on the basis of the needed transitions within the time frame available before 1.5 °C is reached.

Ziervogel et al. (2016) reference the 1.5 °C target and highlight the need for transformative adaptation in order to avoid environmental and social damage. This points to the importance of “regenerative design”, especially in cities, as one of the means for pursuing ambitious mitigation and adaptation targets.

[*Discussion of the difference between integration and mainstreaming? Or as a box or FAQ*]

4.3 Getting to 1.5 °C worlds: transitions and transformative pathways

4.3.1 Comparison of relevant pathways to 1.5 °C worlds with historical trends and social acceptance

This section will assess rates of technological and societal change against pathways to the visions of 1.5 °C worlds, building on Section 4.2 and on Chapter 2. Literature reveals two basic approaches to the question whether rates of technological and societal change are realistic.

The first approach is the analysis, evaluation and extrapolation of historical trends into the future. Such studies sometimes take a narrative approach, collecting, for instance, long-term data on energy use and sources, analyzing the drivers of the patterns observed, and applying the results towards understanding the transition to a low-carbon world (Fouquet 2016). In addition, such extrapolation is done using scenarios and models over relatively long time periods (typically several decades) assuming different growth rates and patterns (Lamb and Rao 2015; Clarke et al. 2014).

A second approach analyzes how technologies have developed over time and contrasts those patterns against quantitative models to understand how contemporary technologies may develop in the future, and whether models are making sound assumptions (Hook et al. 2011). Wilson et al. (2013) conclude that for technologies, models are generally more conservative than historic data suggest. A qualitative strand of this is pioneered by Geels and Schot (2007), who have developed a typology of trajectories of technological change, abstracting from the specific speed of change, and emphasizing the possibility and effects of shocks and other types of discontinuous change. Recently, Geels et al. (2016) also illustrate that energy transitions are associated with wider socio-economic transformations, and that models generally don't represent such processes.

The two approaches reflect different but complementary views on how the past affects the present and the future, and what's to be learned from history. When extrapolating trends, we assume that time progresses forward and that we can learn from the past to understand the direction of technological change in the future. When fitting historical growth patterns into models, the second approach, we assume time has a cyclic character that history can repeat itself, and that patterns of change in the past can predict, to some extent, patterns of change in the future. Assessments of the rate of change will vary accordingly, with extrapolating studies emphasizing the slow, difficult process of change (Fouquet 2016) and fitting studies pointing towards the possible fast speed of change (Wilson et al. 2013).

4.3.2 Mitigation

Section 4.2 has outlined visions of a 1.5 °C world compatible with the targets adopted in the Paris Agreement (UNFCCC, 2015). Chapter 2 presents new pathways that would limit temperature rise to well below 2 °C and 1.5 °C.

This section is a deep-dive into unpacking these pathways, assessing the elements specific to 1.5 °C given current knowledge (Section 4.3.2.1) and going beyond the pathways in exploring the body of literature that would allow for deviations from these pathways, e.g. in terms of allowing additional mitigation potential through disruptive innovation or lifestyle changes (Section 4.3.2.2). Section 4.3.2 is focused on mitigation and thus complementary to section 4.3.3, which assesses adaptation needs and options in different visions of a 1.5 °C world.

4.3.2.1 Unpacking the 1.5 °C pathways: how to reach 1.5 °C worlds

[*The assessment of the pathways towards 1.5 °C worlds for the internal draft will rely on the 1.5 °C scenarios published in Rogelj et al. (2015), who conducted a comparison of 1.5 °C vis-à-vis 2 °C pathways. The numbers will be adapted as the new ensemble of scenarios becomes available. It is also useful to look at the delay scenarios for 2 °C (Luderer et al. 2013) for orientation, as they have similar features as the 1.5 °C ones, in general.*]

The main characteristics of 1.5 °C pathways can be summarized as follows: they are at or below the emissions pathways of RCP2.6 in AR5, and all of them feature carbon budget overshoot (see Chapter 1). Additional emissions reductions are required to move from a 2 °C to a 1.5 °C scenario mainly achieved by (a) more rapid reduction of fossil CO_2 emissions, and (b) BECCS and management of land-use sinks (possibly additional technologies in new scenarios). Emissions need to be net zero by mid-century and net negative thereafter. Almost the entire assumed abatement potential for non-CO_2 GHGs is already exhausted in 2°C scenarios, so little additional reductions are possible in the 1.5°C pathways. Finally, there is almost no room for growth in energy demand (total final consumption): from 350 EJ yr^{-1} in 2015 to maximally 450 yr^{-1} by 2100 (compared to on average 600 EJ yr^{-1} for 2°C).

Based on this, there will be a more detailed assessment of new mitigation elements (compared to 2 °C). In particular, fossil-based electricity generation needs to be phased out earlier than for 2 °C, carbon-free technologies must be ramped up faster, and the share of electricity in final energy rises more rapidly in 1.5 °C-consistent scenarios. This paragraph will thus first discuss the incremental changes for fossil phase out, renewables, nuclear, Carbon Capture and Storage for electricity, and the electricity share in final energy.

Furthermore, there will be a massive increase in electricity for transport, though this does not necessarily exceed the increase in a 2 °C scenario by much. Incremental mitigation in transport compared to 2 °C mainly comes from demand reductions (e.g. modal shift) and an increased use of biofuels in liquid energy carriers (cf. discussion on potential for land use competition in the context of bioenergy in general below). Therefore, currently considered (modelled) options for such additional demand reductions will be assessed, but also options for increasing biofuels sustainably. Section 4.3.2.2 will expand this by examining literature on systemic changes resulting in untapped potentials, which could buy more mitigation in transport. As discussed in Sections 4.4.2.3 and 4.5, technical potentials might often not be exploited because of barriers to implementation related to market structures (e.g. subsidies for conventional transport fuels), financing (e.g. mass transport infrastructures), behaviour and acceptability, as well as systemic effects (path dependency, lock-in, robustness of socio-technical systems).

Concerning industrial and buildings emissions, 1.5 °C scenarios feature emissions of 25% and 50% lower than for 2 °C, respectively, by 2050. Options for realizing these potentials will be assessed, in particular, buildings can have net zero emissions, by integrating on-site renewables (e.g. solar and geothermal) and enhancing efficiency of equipment and insulation. Section 4.3.2.2 will again shed light on whether there is new literature on untapped potentials, which could buy more flexibility to choose between decarbonization options.

Finally, there is a massive increase in literature on negative emissions (Minx et al. 2017). In the light of their increased role in 1.5 °C pathways, their feasibility and sustainability will be given systematic attention in this section – intending to cover all technologies/technology clusters as well as land-based Carbon Dioxide Removal options. Potentials (heat bars across estimates from the literature), costs and side effects for the full set of technologies will be assessed – starting from scenarios, but complemented with bottom-up literature.

4.3.2.2 Discontinuous pathways: additional levers for 1.5 °C

In this Section, the objective is to identify new literature that would allow for disrupting the pathways, e.g. by significantly expanding the mitigation potential in one sector or by shifting systems towards different equilibria that allow for different areas in the mitigation solution space to be explored. The following areas have been chosen as foci for this part of the assessment: innovation, demand-side changes, non-CO_2 GHG reductions and changes in economic systems.

4.3.2.2.1 Innovation – beyond learning curves and technology diffusion assumptions in scenarios

Technological change can go slowly, but when tipping or inflection points are reached, also all of a sudden much faster than most people, and models, expect. We have seen a modest version of that in the cost reductions deployment rates of solar and offshore wind energy recently, which exceeded almost all expectations. But changes can also happen more quickly because of enabling technologies. Rapid and disruptive technological change is ongoing, such as in the fields of the Internet of Things, Artificial Intelligence, self-driving cars, robotization, or sensors. Such new technologies can have deep impacts on emissions pathways.

The narrative scenarios of technological innovation in the future will be assessed for their mitigation potential. Some expect innovation to bring economic growth and solutions to a variety of social issues including climate change. Those, admittedly speculative, scenarios generally follow the following narrative: 1) general purpose technologies, in particular ICT develop and are applied by innovators to various fields such as finance, medical, manufacturing, cars, buildings, energy etc. creating new industries and business models; 2) innovators receive feedback from such field applications and advance ICT further; 3) ICT eventually brings about destructive innovation beyond the boundaries of existing fields.

The complexity theory literature will be assessed to find pointers for how the dynamics of technology and innovation can be put to work for 1.5 °C pathways and applications in adaptation. Conditions for a new technology to emerge, such as sufficient accumulation of prior technologies and satisfaction of adjacent possibilities, are assessed.

4.3.2.2.2 Demand side (especially difficult-to-decarbonize sectors like transport) – lifestyle changes etc.

Individual choices, preferences, and behaviour have major implications for anthropogenic climate change and affect the ultimate effects of mitigation and adaptation strategies (Dietz et al. 2013; Hackmann et al. 2014; ISSC and UNESCO 2013; Sovacool 2014; Weaver et al. 2014; Vlek and Steg 2007). In fact, most if not all mitigation and adaptation strategies that aim to realise economic, physical or technological changes involve changes of behaviour and require public support. Substantial modification of a wide range of actions by many different people is needed. Such actions include the adoption of renewable resources (e.g., solar power), the implementation of resource efficiency measures in buildings (e.g., insulation, water saving devices), the adoption and use of sustainable innovations (e.g., electric vehicles) and resource-efficient appliances (e.g., energy-efficient domestic appliances), and changing user behaviour (e.g., cycle rather than drive) (Steg 2016). People need to accept proposed changes and policies, and use new technologies and infrastructure in the intended way.

The focus will be on behavioural patterns that have a substantial potential for carbon emission reduction or adaptation, thereby considering the plasticity of the behaviour (i.e., likelihood that the targeted behaviour will be adopted). For this purpose, it is important to identify behavioural wedges (Dietz et al. 2009) and related time scales (i.e., immediate responses involving decreased use of goods and services versus responses in the long term such as replacement of technology). The first wedge targets options with substantial potential for carbon emission reduction, such as the adoption and use of sustainable technologies (Dietz et al. 2009). These have a high potential, as they have relatively low behavioural costs, and will demonstrate that efforts are effective which will motivate people to engage in behavioural change as well. Adopting such behaviour may strengthen environmental self-identity, which motivates people to act sustainably in subsequent situations in order to be consistent (van der Werff et al. 2014). In the meanwhile, new technology, policy and institutions can be developed that promote and facilitate further changes (further explained later). However, one needs to not only consider adoption and use by end consumers, but also political behaviour and behaviour in organisations that can advocate, support, or help block emissions at various levels.

Lifestyle changes need to be complemented by effective and innovative policies that ban highly emitting technologies (e.g. fossil fuel cars, poorly insulated buildings) and push for the adoption of low carbon technologies, for example net zero energy buildings or electric vehicles. This is normally achieved with technical regulations for equipment, cars and buildings. Additional attention is now on urban planning policies as new building location, public transport infrastructures and local energy sources can be optimise to have net zero energy districts. Finally, financing is critical in this transformation. Options to strengthen the financing of low carbon technologies and solutions and a more detailed discussion of policies will be presented in Section 4.5.

4.3.2.2.3 Non-CO_2 GHGs

One reason why negative emissions feature so importantly in the energy sector of 1.5 °C consistent pathways is not that such a strategy buys time to implement other mitigation options, but that there are other sectors which are next-to-impossible to decarbonize sufficiently quickly. Outstanding in this respect are the non-CO_2 GHG emissions that are mostly associated with our food system and, in particular, livestock. While the mitigation potential has been relatively well researched from the supply side perspective, potentials arising from demand side measures is still under-researched and therefore probably underestimated (Smith et al. 2013). Rivera-Ferre et al. (2016) provide a review of both supply (improving nutrient and carbon cycling on land and in livestock, enhancing input capital and labour productivity, advancing market mechanism and using alternative fuels) and demand-side (reduction of meat consumption and wastage, reduction of lifecycle emissions and voluntary standards and labelling) mitigation measures (going beyond non-CO_2 GHGs) and their associated potentials and actively look for synergies with adaptation strategies. They conclude that a mixture of measures will be needed to exploit most of the mitigation potential in this sector. This again could alleviate the need for negative emissions to offset a large amount of non-CO_2 GHGs.

4.3.2.2.4 Economic systems

Chapter 2 indicates that the 1.5 °C scenarios maintain the drivers for economic growth that are prevalent in many political systems at this time. If, however, this paradigm would change towards an economy of sufficiency, the terms would change completely (Mölders et al., 2014; Princen, 2005). This literature will also be explored for relevance for 1.5 °C.

4.3.3 Adaptation (based on input from chapter 3 on risks, exposure, vulnerability)

IPCC AR5 defines adaptation as "the process of adjustment to actual or expected climate and its effects, in order to either lessen or avoid harm or exploit beneficial opportunities" (IPCC, 2014b, p. 76) and identifies limits to adaptation as climate impacts rise, especially with future warming beyond 2C. AR5 also underlines the importance of developing adaptation in consonance with sustainable development to enable the enhancement of future options - the rationale for the potential convergence of mitigation and adaptation pathways to meet the 1.5 °C goal (UNFCCC 2015a; IPCC 2014).

Adaptation implementation encompasses a variety of strategies, actions, and behaviours across scales that make human and managed, biological and physical systems more resilient to climate change, within a holistic framework of disaster risk reduction and sustainable development (IPCC 2014) UNISDR, 2016, UN, 2015). It may focus on independent or joined-up strategies to: reduce vulnerability, reduce exposure and sensitivity to climate impacts, strengthen adaptive capacity to address current and emerging climate risks; enable transformative adaptation to 'build back better'; reduce the impact of maladaptation and sometimes enable hazard modification (Revi et al. 2014) (Satterthwaithe et al., 2016, Pelling, 2010). It is typically place-, scale- and context-specific, with no single approach for reducing risks appropriate across all settings; hence, closely allied with the localisation of Agenda 2030, and the principles of leaving no-one, no-place and no-ecosystem behind (IPCC 2014).

There are many different (and contested) approaches to managing the risks of climate change through adaptation, and enabling its convergence with sustainable development and poverty reduction (Sherman et al. 2016). Early research and interventions focused on adaptations responding to the impacts of experienced and projected climate change, often independent of mitigation (IPCC, TAR, AR4). Adaptation is more recently, is viewed as a complementary and conjoint set of interventions with mitigation and its associated co-benefits (IPCC 2014), especially in the context of 1.5 °C (Roberts, 2017). It is also being increasingly seen as a component of an ensemble of broader disaster risk reduction, extreme event response, resilience building and sustainable development strategies (Field et al. 2012) (UNISDR, 2015, UN, 2015).

This section will: examine what 1.5 °C means for adaptation; identify key systems at risk and how they have to adapt to these risks and extremes; take stock of current commitments to adaptation and how far they may enable a respond to 1.5 °C; examine different perspectives on how to adapt to 1.5 °C, and; document the costs, benefits, and barriers of doing so.

4.3.3.1 What does 1.5 °C mean for adaptation?

- This section will look at unique and threatened systems and sectors at risk, that will need to adapt to 1.5 °C, including tipping points (e.g. the Arctic, monsoon) and vulnerable hotspots (semi-arid regions, cities) Arctic and extreme events. [*Box on sectors and systems?*]
- Risks to 1.5 °C-related adaptation pathways will be examined though a lens of vulnerability. Are key systems and regions vulnerable to these pathways? What are the impacts of key sustainable development dimensions (e.g. poverty, food security education, health, basic services, sustainable cities, sustainable production and consumption) (Lutz and Muttarak, 2017); other social and economic vulnerabilities and inequality; governance, institutions and markets; technology and locations?
- Assessment of exposure reduction, relocation and migration strategies and response to extreme events within 1.5 °C adaptation pathways; and the positive and negative impacts on poverty, inequality, economic and social vulnerability and hence, sustainable development.
- Assessment of how individual, community, and consumer behaviour impacts vulnerability, and hence adaptation pathways (Wise et al. 2014).
- An assessment of the positive and negative effects of mitigation pathways, their interaction and synergy with adaptation pathways, with a specific emphasis on differential exposure and vulnerability.

4.3.3.2 How far do adaptation commitments get us in managing the impacts of 1.5 °C?

- Stocktaking of regional/global adaptation commitments: This section will use the growing peer reviewed literature documenting and examining the state of adaptation: globally and across regions and scales (Araos et al., 2016; Austin et al., 2016; Lesnikowski et al., 2016; Lesnikowski et al., 2015; Lwasa, 2015; Sud et al., 2015; Robinson, 2017). It will assess how NDCs, NAPs and regional adaptation pathways are defined; adaptation needs identified and commitments made;1.5 C adaptation preparations is proceeding and gaps in these processes? Are adaptation commitments looking at below 2 °C or beyond to 1.5 °C and what does that entail?
- Stocktaking of other commitments relevant to adaptation to 1.5 °C (e.g. the SDGs, Sendai framework and the New Urban Agenda). It will assess what 1.5 °C-related risks and systems are being targeted, and what commitments have been pledged (UNISDR, 2015, 2017, UN Habitat, 2016)
- An assessment of the residual impacts of current mitigation and adaptation commitments with respect to adaptation pathways to 1.5 °C world, and response options to them?

4.3.3.3 Pathways to 1.5 °C adaptation

4.3.3.3.1 Sustainable development and adaptation to 1.5 °C

Sustainable development is central to managing the risks posed by climate change. This reflects the potential impacts of climate change on sustainable development (Denton et al. 2014), with researchers challenging 'development as usual' as an option (Inderberg et al. 2014; Olsson et al. 2014) and calling for development pathways that have adaptation outcomes (Sherman et al. 2016).

There is a growing recognition that meeting development aims sustainably will have co-benefits such as building adaptive capacity (Inderberg et al. 2014; Schipper 2007) as well as reducing structural drivers of vulnerability (Tschakert et al. 2013; McGray et al. 2007). Sustainable development underpins what Eakin et al (2014) term 'generic adaptive capacity' associated with deficiencies in basic human development needs (e.g. health, education, livelihood security, mobility), and constrained opportunities and freedoms, which shape inherent vulnerability.

This section will assess what risks of 1.5 °C that sustainable development can offset. Likewise, it will examine how coordinated climate change adaptation, disaster management, reconstruction and resilience building actions can lead the way to sustainable development?

4.3.3.3.2 Transformational adaptation and 1.5 °C

This section will examine in what contexts (risks, systems, regions and sectors) transformational adaptation might be required to address the impacts of 1.5 °C (it will further assess the implications of going from incremental to transformational adaptation (link to 4.3.3.4 and 4.4.4.3).

4.3.3.3.3 Top-down and bottom-up approaches and cross-scale integration

Diverse perspectives on top-down, bottom-up and cross-scale adaptation strategies have been proposed in the literature. This section will examine each in the light of 1.5 °C, across the following themes:

- Local and traditional knowledge systems: In many contexts, particularly rural and Indigenous communities, LK/TK systems underpin adaptive capacity to manage climate change and a variety of stresses (Savo et al. 2016) (Pearce et al., 2015). These knowledge systems are being affected by climate change and development pathways, with implications for how 1.5 °C, or higher, will be experienced and responded to (Nakashima et al., 2012; Ford, 2012; Maru et al., 2014).
- Ecosystem based adaptation: Ecosystem based adaptation practices need to evolve in a 1.5 °C world to increase resilience to ecosystems that will be more fragile and vulnerable and at the same time, support the people that depend on services from these ecosystems..
- Community based adaptation: Community based adaptation strengthens local capacities and empowers populations to better respond to climate related risks (Forsyth 2013; Reid et al. 2009; Ensor et al. 2016). Community based- and ecosystem-based adaptation work synergistically to enable disaster risk reduction,

resilience building and climate adaptation (Schipper et al. 2014).

- Adaptation pathways: This section will discuss the connection between bottom-up disaster risk management, sustainable development, and adaptation, and how synergetic mitigation and adaptation pathways can reduce exposure, vulnerability and impact.

4.3.3.4 Costs, benefits, trade-offs and risks of adaptation

4.3.3.4.1 Costs and benefits of adaptation

Costs and benefits of adaptation and mal-adaptation, opportunity costs of adaptation limits associated with 1.5 °C

4.3.3.4.2 Trade-offs between adaptation pathways

Adger (2016) forefronts ideas of fairness and justice when assessing trade-offs between adaptation pathways: "the focus on risk assessment and resilient infrastructure has the potential to ignore deeper issues such as the distribution of the burden of risk and the potential for resilience to be built within the underlying social-ecological systems". He also argues that "uncertain costs, uncertain and incommensurable outcomes, entrenched vested interests, lack of public engagement and complex environmental and social dynamics" challenge adaptation actions which are taken by multiple actors and for various, often contradictory motives. This section will examine trade-offs associated with adapting to 1.5 °C, and negative effects that mitigation pathways associated with 1.5 °C might have for adaptation.

4.3.3.4.3 Risk management and risk perception

The risk perception literature identifies ways in which perceptions of climate variability/resource scarcity shapes response behaviour, with adaptation being one kind of response. A rapid increase in the literature tends to focus on mismatches between risk perception and actual data; fewer papers are beginning to highlight psychological barriers to adaptation (Burnham et al. 2016; Rice et al. 2015) and how they impact risk management behaviour.

4.3.3.4.4 Adaptation barriers and limits to 1.5 °C

Adaptation planning, financing, and implementation are constrained by several factors, ranging from physical (Adger et al. 2007), financial (Patnaik 2010), social and cultural (Jones and Boyd 2011; Ahmed and Fajber 2009), institutional, awareness-related and technological barriers (Adger et al. 2007), and cognitive (Grothmanna and Patt 2005; Singh et al. 2016).

These barriers not only limit the available response space (range of opportunities available to undertake coping or adaptive strategies, (Singh et al. 2016) and constrain adaptive capacity, but also lock people and systems into pathways that can accentuate, consolidate or create barriers (Adger et al. 2007; Biesbroek 2013; IPCC 2014). The path-dependent nature of the institutions governing natural resources and public goods is a deep driver of barriers and limits to adaptation (Evans et al. 2015). Barriers are related to human actions or decisions, and, as opposed to limits, which can be manageable through concerted effort, creative management, resource reprioritization, and behavioural changes. It is critical to note that while barriers are considered surmountable or mutable, limits are understood as more absolute or unsurpassable.

4.3.4 Solar Radiation Management

[Either as a box or part of the text – tbd in consultation with other chapters]

Section 4.2 indicated that under some circumstances, the use of SRM could benefit at least some countries or actors. SRM could reduce the global risks of climate change related to temperature rise (Keith and Irvine 2016; Irvine et al. 2016; Keith et al. 2016; Izrael et al. 2014), but also presents a number of risks and concerns (Robock 2016; Visioni et al. 2016; Smith et al. 2017).

Several SRM technologies have been proposed to mitigate GHG forcing:

- Stratospheric aerosol injection (SAI) (Crutzen 2006; Keith and Irvine 2016; Irvine et al. 2016) which would involve injecting of sulphates or other particles into the stratosphere continuously using airplanes, tethered balloons, or other delivery technologies;
- Marine cloud brightening (MCB) (Latham et al. 2014; Wang et al. 2011) which would involve spraying sea salt or other particles into marine clouds, making them more reflective;
- Cirrus cloud thinning (Jackson and Webster 2016; Muri et al. 2014) which would thin cirrus cloud coverage to allow more outgoing infrared radiation to escape into space;
- Space mirrors (Angel 2006) which can be set in orbit in order to reflect sunlight back into space;
- Ground-based albedo modification - white roofs (Akbari et al. 2012; Jacobson and Ten Hoeve 2012) which would enhance surface albedo and more reflective crops (Irvine et al. 2011) which would involve planting crops with more reflectivity.

This section will cover social issues and risks created by SRM, including “moral hazard” (McLaren 2016), ethics (Svoboda 2016; Wong 2014; Quaas et al. 2016), geopolitical conflict over testing and deployment (including unilateral deployment) and other political conflicts (Lambini 2016; Weitzman 2015). Furthermore, this chapter will discuss changes in solar power resources (Smith et al. 2017). Deployment of SRM can also lead to health risks, connected with sulphur aerosols deposition (Effiong and Neitzel 2016), increase of surface ozone concentration and reductions in surface UV-B irradiance (Nowack et al. 2016; Pitari et al. 2014). However, careful deployment of certain type of materials could help avoid negative effects of SRM on the ozone layer (Dykema et al. 2016; Keith et al. 2016). Cost assessments for different SRM technologies will also be discussed (Harding and Moreno-Cruz 2016; Moriyama et al. 2016; McClellan et al. 2012).

A “Termination shock” or “termination effect” has been discussed in numerous studies (Robock 2016; Izrael et al. 2014; Jones et al. 2013). All of them concur that a sudden stop of SRM deployment will lead to rapid temperature rise toward the levels they would have reached without SRM. However, some recent studies indicated that risks and benefits of SRM depend on assumptions about implementation. They show that termination effect could be excluded or reduced under well-orchestrated deployment and cessation of SRM (Keith and MacMartin 2015; Reynolds et al. 2016), though this would require strong governance and institutional arrangements.

Neither SAI nor MCB have been demonstrated in real-life conditions or at a large scale so far. However, studies indicate that such systems could be developed and deployed in the next decade (McClellan et al. 2012; Ryaboshapko A.G. 2015; Davidson et al. 2012).

4.4 Sectoral and regional implications of transitions and transformative pathways

4.4.1 Assessment framework

Assessing the implications of strengthening the global and regional response to a 1.5 °C warming limit critically depends on an assessment framework that is straightforward, respects “common but differentiated” values, and allows for comparison across regions. It also needs to embrace the complexity and diversity of economic, social, environmental drivers of climate mitigation and adaptation, and provides broad brush estimates of the relative costs and benefits of the multiple mitigation and adaptation pathways, in the context of sustainable development and poverty reduction.

It needs to be an integrated frame that addresses both mitigation and adaptation and, where possible, synergies between the two. It needs to be a longitudinal frame that provides a sense of the relative progress of various pathways across the short-, medium- and long-run, over the century. Finally, it should be possible to compare both SSP and non-SSP based modelling outcomes to examine the potential policy, implementation and institutional implications of continuous or transitional vs. disruptive change or transformations.

The proposed frame is built around five broad clusters of variables that map onto the Sustainable Development frame (UN, 2015). An indicative set is:

- Demographic: total population, urban population and dependency ratios
- Economic: economic output and consumption share
- Social: per capita income and proxy estimates of inequality
- Environmental: land use and cover changes
- Climate and Energy: Carbon equivalent and GHG emissions, primary energy and end-uses, carbon prices
- Costs and Benefits: broad estimates of the costs and potential benefits of mitigation and adaptation measures
- Regional representation: map-based representation of key mitigation and adaptation priorities and interventions

This will enable in the case of SSPs/IAMs an investigation of 1.5 °C-compatible RCPs. The methodology for the non-SSP models will need to be determined.

[NOTE: this framework will be built for the FOD based on input from an assessment of various modelling frameworks and literature under publication with the support of and consultation with Chapter 2 and Chapter 3 teams].

4.4.2 Sectoral implications of 1.5 °C pathways

This section explores sectoral implications of global and regional transformation pathways towards 1.5 °C.

4.4.2.1 Energy (including electricity)

As described in Section 2, different visions for a world stabilizing temperature increase at 1.5°C are associated with an energy mix and demand side management very different from today. In the electricity sector, the renewables share will be at XX% in a middle-of-the-road scenario of which XX% is biomass, nuclear still contributes XX%, fossil fuels are completely phased out, except for XX% with CCS. There is almost no room for growth in energy demand, requiring technological and behavioural advance on the demand side as well.

Comparing this to today's situation illustrates the transformation need that this vision implies. Global energy demand has continued to increase to 13,700 Mtoe in 2014 and 2015, though at less than half the growth rate in 2014 than in 2013. While non-OECD countries experienced demand growth of 2.3%, OECD countries' demand actually decreased by 0.7% with no further growth in 2015 (IEA 2016). Fossil fuels' contribution to total primary energy supply decreased to 81.2% with oil production still being dominant at 31%, followed by coal (29%) and natural gas (21%). Among non-fossil sources, biofuels and waste accounted for a share of 10%, with hydro and other renewables (wind, solar thermal, solar PV, geothermal) at 2% (despite accelerated growth) each and nuclear at 5% (IEA 2016). *[NB: These introductory paragraphs may need to be adapted when the scenarios become available from Chapter 2. If this is already covered in Section 2, we would just start with a cross-ref in the first sentence here.]*

While in Section 4.3.2 the pathways with their different mitigation options are unpacked, this section goes more deeply into specific implications and strategies for the energy sector (e.g. on idling systems for RE) and how they could be realized, which will context-specific (e.g. the Global South versus the industrialized countries). Some countries, mainly in the Global South, are jumping directly into renewable energy generation (with smaller or lesser generation from fossil fuels) without passing through the fossil fuel electricity generation trajectory that the global North and middle-income countries have described. Countries with a low level of electrification use renewable energy sources in the form of isolated or distributed generation systems, and would only use diesel or other fossil fuel generation as a back-up.

Such energy sector analysis applies for mitigation as well as for adaptation. To see this for adaptation, consider the vulnerability of RE to extreme events. For example, hydropower stations in Central America and the Caribbean can go completely offline during such an event, so the risk that fossil generation takes over in that case must be contained. For a mitigation example, the enormous energy efficiency improvements implied by the 1.5 °C target will be harder to achieve in the global South, where the existing market of appliances usually relies on discarded appliances of the global North.

Furthermore, the 1.5 °C target makes the energy sector special in the sense that it will not only need to cover energy demand, but also provide for negative emissions (see also Section 3.2). Bioenergy will be an important part of the energy mix in a 1.5 °C world. On the one hand, these scenarios will feature to a large extent an overshoot of emissions/temperature increase in the medium run before returning to the target. In most IAMs this will be achieved by combining bioenergy with CCS (BECCS), although some manage without. What we see in the 2°C and 1.5 °C scenarios, however is that even if we exclude the possibility of CCS (and thus BECCS), we still see a large portion of bioenergy in the system because it then needs to be used to decarbonize the transport sector more rapidly. Bioenergy will thus warrant a separate paragraph.

4.4.2.2 Industry (including waste/recycling)

Industry comprises material and manufacturing industries, such as iron and steel, cement, aluminium and other non-ferrous materials, the (petro-) chemical industry and the pulp and paper industry. The direct and indirect emissions of such industries, including steel, cement and chemicals, amounted to around 30% of global GHG emissions in 2014 (Olivier et al. 2016). Industrial GHG sources are distributed globally and scattered over numerous companies, although this varies: in steel and chemicals production, large, multinational companies dominate the market while in cement, smaller companies are important too.

For global temperatures to remain under 1.5 °C, industry will need to fully operate drastic changes in three directions:

- Bio -based feedstocks, electrify processes, and/or capture and store any CO_2 emissions by 2050 (Åhman et al. 2016).
- Material substitutions between high-carbon products and substitutes made up with renewable materials (wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics)
- Increase of the rate of recycling of material, development of circular economy industry (Lewandowski and Mateusz 2016; Linder and Williander 2017) (Clift and Allwood, 2011) planned obsolescence (Bidgoli 2010) (Bulow Jeremy 1986) and, more generally deployment of industrial ecology concepts.

Pathways for 1.5 °C in Integrated Assessment Models generally provide less detail for industry compared to electricity or transport. Nonetheless, we will provide a discussion of the sectors that contribute most to the globe's GHG emission (iron and steel, cement, chemicals, pulp and paper) and all other type of prospective study on the industrial transition (Crassous et al. 2008). Triggering a fast low-carbon transition will need to deploy infrastructure programmes, and energy efficiency programmes will be material-intensive, while the production of these materials will remain carbon-intensive.

An important dimension to facilitate deep decarbonization in energy-intensive industries on the scale to achieve a 1.5 °C requires addressing competitiveness, fairness, sustainable development, and technology transfer (Åhman et al. 2016). The development of appropriate policy approaches to address the mitigation and transformation challenges in these industries is critical for the success of their decarbonization. Bottom-up, technology-based (including R&D cooperation), and sector-based approaches, along with border carbon adjustment are some of the approaches on the table (Cosbey and Tarasofsky 2007; Fischedick et al. 2014).

4.4.2.3 Transport

Decarbonising transport is primarily a process of reducing the need to travel by motor vehicles and by removing oil from transport vehicles. Creating more walkable centres in cities has been shown to significantly reduce cars and the need to travel. Transit systems are now growing faster than car movements but will need to accelerate further within cities and between cities where air travel can be reduced by fast rail. Freight trends are beginning to show reductions as consumption is dematerialised. Smart communication technologies are likely to continue improving and will be much needed to replace a higher proportion of business and family travel. Removing oil is mostly happening by electric vehicles – cars, bikes, buses, trains, even planes – driven mostly by rapid reductions in cost of batteries. Solar-based recharging of batteries for vehicles will need to become the majority fuel for transport to achieve 1.5 °C. Biofuels are likely to grow mostly for agricultural vehicles and aircraft. Both the reduction in need for mobility and the reduction in oil-based vehicles will be assisted by smart control systems and by inclusive policies that enable co-benefits in such changes.

4.4.2.4 Buildings

The energy consumption and CO_2 emissions of the global building stock (residential, commercial and industry) represents XY% of the total.

New buildings can be constructed with the Net Zero Energy Concept (NZEBs) (or NZCB, i.e. carbon neutral) allowing for a smooth transition from current building codes levels to NZEBs. In order to achieve the 1.5 °C scenario, the transition should happen ASAP. This will also to avoid the lock-in effect. New construction NZEBs are cost-effective in all the climatic zones. The needed technologies already exist. To be further investigated are costs of having new buildings to be energy positive. A new concept emerges with buildings as carbon sinks.

Buildings are mostly inserted in urban contexts, therefore if it is possible to have NZEBs at the single building level, this could be achieved at the district level.

In cold climates electrification (provided CO_2 free electricity is available) and use of biomass are essential to reduce fossil fuel consumption in buildings.

Attention must be paid to the equipment inside the buildings as with the decrease of heating and cooling due to progresses in insulation IT, lighting and appliances may become the major loads. Also, life style and consumer behaviour are concept to be further strengthened.

In most of the developed countries the major issue are existing buildings, which may still be used in 2050 and beyond. Retrofit/refurbishment of existing buildings is essential especially in HICs and other economies (e.g. former Soviet bloc counties). Deep retrofits are needed to avoid lock-in effect. The key question is how to finance building retrofits as these are not always cost-effective (depending on the carbon price) and require large investment. Building owners or occupiers face barriers to investments

Buildings will be an integral part of the new electric systems, by producing, storing and selling energy. Consumers will become prosumers. Buildings have an active role in enhancing adaptation to climate change. Urban heat islands can be mitigated with cool and green roofs and green facades.

Policies and financing mechanisms are key for the transition to NZEBs and low carbon buildings.

4.4.2.5 Land: agriculture, livestock, forestry

Considerably more carbon is stored in the world's soils, peatlands, wetlands and permafrost than is in the atmosphere and land use is important to the prospects of stabilizing temperature increase at 1.5 °C (Davidson et al. 2006). Land not only provides a source and potential sink of CO2, but is also central to adaptation, for example in coastal zones (Schleussner et al. 2016) and through agriculture and forestry. While some of the land-based mitigation options such as reducing rates of deforestation and forest degradation (REDD+) or substituting bioenergy for fossil fuels avoid emissions, others are specifically needed to reach a 1.5 °C because of the overshoot such pathways are associated with.

Among such land-based "negative emissions" mitigation options, also called Carbon Dioxide Removal (CDR) (see also Section 3.2), bioenergy combined with carbon capture and storage (BECCS) and afforestation currently feature most prominently in the scenarios (see also Section 3.2.1). However, BECCS and afforestation are contentious in the debate because of potential competition for land to achieve other sustainable development goals such as food security for all and safeguarding of terrestrial ecosystems (Haberl 2015; Williamson 2016) and the labile nature of carbon sequestrated in plants and soil at higher temperatures (Ågren 2000; Davidson et al. 2006; Wang et al. 2013). Managing the trade-offs between increasing biofuel production and the negative climate and ecological consequences of growing and processing bioenergy crops is possible, but requires a location specific strategy (Jonker et al. 2017).

Other complementary approaches such as biochar, soil carbon sequestration and enhanced weathering (see also Section 3.2.2) are land-based but do not directly compete with food production and could have substantial co-benefits in terms of raising crop yields (Smith et al. 2016; Smith 2016).

The AR5 which focused on 2 °C stabilization pathways at the lower end of the considered spectrum found a LULUCF mitigation potential of up to 10.60 GtCO2eq yr^{-1} in 2030 for mitigation efforts consistent with carbon prices up to 100 USD/tCO2-equivalent. This included both supply and demand side measures, with the main sources of emissions addressed being deforestation and agricultural emissions from livestock, soil and nutrient management, while the demand side measures (e.g. waste reduction, diet shifts) was flagged as under-researched (Smith et al. 2014). In 1.5 °C pathways emissions reductions from the AFOLU sector range from xx%-yy% depending on the underlying assumptions about population and economic growth, technical change, etc.

The potential for sequestering atmospheric CO2 in processes that simultaneously restore the large swathes of degraded land globally has been explored as a transformative climate change intervention. Smith et al. (2007) report that restoring degraded grazing land could reduce atmospheric CO2 by similar magnitudes to forest and crop interventions. Innovations in livestock management, the use of fire regimes in Savannah and rangeland ecology offer the potential to remove the assumed trade-off between soil carbon restoration and stocking densities (overgrazing) and shift the balance of carbon in above-ground biomass, soil carbon and animal protein in support of CO2 sequestration, reduced atmospheric CH_4 and sustainable development (Archibald and Hempson 2016; Venter et al.).

Henderson and colleagues evaluated three rangeland management innovations and found

- Optimization of grazing pressure could sequester 148 Tg CO_2 yr^{-1}.
- Legume sowing enhanced soil carbon and sequester 203 Tg CO_2 yr^{-1}. However, N_2O emissions from legumes were estimated to offset 28% of its global C sequestration benefits, in CO_2 equivalent terms.
- N_2O emissions from N fertilization exceeded soil C sequestration, in all regions (Henderson et al. 2015).

Land use change is one of the key factors responsible for greenhouse gas emissions in the whole plants (Ziervogel et al. 2008). Initially, land use imposes stresses on the potential for land-based sequestration. Adaptation consistent with 1.5 °C pathways must to be checked for loss of sequestrated carbon when forests are transformed into agricultural land (Guo and Gifford, 2002).

According to FAO, the four main crops planted in the world are wheat, maize, rice and soybean. Thousands of experiments have been performed with these species under elevated CO_2, high temperature, and drought – the three main climate change-related biophysical factors affecting plants. Meta-analyses found that at 2 °C local warming, wheat, maize, and rice will decrease yield, but that this could be converted into a 7-12% when adaptation measures were taken (Challinor et al. 2014). The limits of adaptation, and associated losses, appear to increase above 2 °C. If these results are correct, this means that agriculture is likely to reach a threshold as temperatures of 1.5-2 °C.

4.4.2.6 Water

Different visions for a world stabilizing temperature increase at 1.5 °C will have different water supply and demand requirements. For the electricity sector, according to the different scenarios presented in Section 4.4.2.1, water consumption patterns will look like [*add water demand requirements for different sectors, and appropriate text on cooling technology for adaptation*] (Fricko et al. 2016). Here we also consider the water demands of bioenergy (Gerbens-Leenes et al. 2012), which we can extrapolate based on the mitigation and energy use scenarios in XX.

Water supply will also change as there is less snow melt, groundwater. [*still to add: water supply sources, how they will change*] (Fricko et al. 2012).

These changes will present challenges to the different sectors that will need to be considered. Areas of the world that are still water constrained might face increased challenges for their water and sanitation indicators, while in other area, lifestyle and behavioural changes in terms of water consumption will play a role. Oceans, ecosystems and watersheds will also be affected in a 1.5 °C world and this section describes some of the measures that can be taken. For example, integrated watershed management efforts (which can include the energy, agriculture, industry, land, and food sector primarily) will need to strengthen governance structures ensuring needs are met without depleting water supply or causing increased damage to the watershed and the biodiversity and social and economic sources it supports.

4.4.2.7 Food

The manner in which people produce, process and transport food is responsible for greenhouse gas emission and is also affected by elevated atmospheric greenhouse gases and higher temperatures (Krey et al., 2012). Anecdotes from food secure countries suggest that that humanitarian imperative of enhancing global access to sufficient food holds the potential to undermine or contribute to mitigation and adaptation pathways required for a 1.5 °C world (Belz 2004; Ziervogel et al. 2016) (Berkhout, 2004).

A food system comprises the “dynamic interactions between and within biophysical and human environments which result in the production, processing, distribution, preparation and consumption of food,” (Gregory et al. 2005). Food systems underpin the food security of individuals, households, and nations by affecting food availability, accessibility, utilization, and stability (Ericksen, 2008a; Ingram, 2009). Stresses and changes to each component of a food system co-occur and interact in numerous ways with implications for food security (Ingram, 2010). Factors affecting food availability include domestic production capacity and elements of food distribution and processing, such as reliable import capacity, presence of food stocks, availability of social protection measures, transportation infrastructure and, when necessary, access to food aid.

The elevation of CO_2 concentration is expected to change the composition of food (DaMatta et al. 2010). For example, wheat and sorghum grown under elevated CO2 have been shown to differ in protein content and composition (Högy et al. 2009; De Souza et al. 2015). The impact of elevated temperatures on food systems extends far beyond CO_2 effects on plant photosynthesis, and includes altered evapotranspiration rates, relative photosynthesis and respiration rates in crops the prevalence of disease and disease vectors, the frequency and intensity of droughts, damage caused by wildfires and phytosanitary implications.

The development of new varieties or genetically modified crops offers one means of buffering the food production system against anthropogenic warming (De Souza et al. 2016). As a central principle, pathways, whether socio-economic, socio-technical or socio-ecological, leading to a 1.5 °C world need to ensure access to sufficient food or sufficient quality, if they are to be durable. Considerable potential exists for innovation in the manner in which food is produced and accessed (Henderson et al. 2015) [*further examples from rangeland ecology, rice production etc. needed*]. Change to these systems is subject to political influences and competing value systems, and requires an alignment of economic incentive, technology and politics (Cote and Nightingale 2012). Transformational socio-economic pathways can combine food systems that produce fewer greenhouse gases, or even sequester atmospheric CO_2, with changes that enhance income to farmer and alleviate malnutrition and poverty (Berkhout, 2004).

While impacts on food production are often the most readily recognizable climate change impact on food systems, low-income countries are particularly vulnerable with regards to food accessibility, utilization and stability. Transportation disruptions caused by extreme events can disrupt food accessibly by increasing prices; warming temperatures can increase post-harvest loss in storage. Adaptation focusing solely on one component of the food system could have little to no impact on food security by neglecting sensitivities which arise further down the food system (Ingram, 2010). Adaptation efforts focused on food systems must consider how climatic shocks and corresponding interventions will affect multiple elements of food systems and food security (P Ericksen, B Stewart, J Dixon 2010).

4.4.2.8 Services (incl. health, education)

The services sector is a key driver of regional economic development, productivity and in many regions, employment. It includes crucial human services like health, education and governance that form the bedrock of sustainable development, poverty and vulnerability reduction. One of the most effective adaptation strategies in DCs is the provision of universal basic infrastructural (energy, water, sanitation, drainage and waste management) and social services (health, education and social protection) to reduce overall and hence climate vulnerability (IPCC, AR5). Similarly, the introduction of energy efficiency, the use of renewable energy and improved energy services, is relatively easy to implement in the services sector.

4.4.2.9 Air quality

4.4.3 Regional and local implications

In keeping with the principle of differentiation, a broad bush assessment of the regional, national and local implications of 1.5 °C pathways will attempt to interrogate the literature across scale and geographical regions, to provide insight into regional differences and implementation priorities.

4.4.3.1 Regional

This will be assessed by IPCC/WMO region.

4.4.3.2 National

Generic assessment of NDC, NATCOMs and NCAAPs where available.

4.4.3.3 Sub-national

Provincial/state/city: critical level for implementation.

4.4.3.4 Other scales will be identified through literature review

From individual behaviour, through consumer group/community to settlement scale.

4.4.4 Assessment of global implications of pathways

4.4.4.1 Assessment of SSP models – global

The global assessment of adaptation and mitigation pathways will be undertaken based on the framework described in Section 4.4.1 using relevant SSPs, based on 1.5 °C viable RCP runs. It is anticipated that this dashboard will be presented as a figure, building on the AR5 experience.

4.4.4.2 Assessment of non-SSP models

The assessment of non-SSP models will be undertaken after a mapping of 1.5 °C relevant models is undertaken and an integrated assessment framework is attempted to be populated. This will be undertaken for the FOD

4.4.4.3 Spill-overs, distribution, cost, benefits/"cost-benefits" and co-benefits analysis (adaptation and *mitigation)*

First, a synthesis of the costs of mitigation and adaptation in the framework of the Shared Socioeconomic Pathways (O'Neill et al. 2014; van Vuuren et al. 2014; Rothman et al. 2014) is conducted. This explicitly considers that there will be (positive and negative) interactions (negative ones henceforth called trade-offs) that will not emerge from the analysis if different options to mitigate and adapt are assessed in isolation. The synthesis of trade-offs between mitigation and adaptation will be based on the insights from Sections 4.3.2 and 4.3.3.

The assessment will also look different when different futures materialize – both socio-economically and climatically. For instance, in a very fragmented world with high population growth, low levels of education and poorly managed urbanization, challenges to mitigation and adaption will be high, whereas in a world with more rapid growth, but less regional rivalry, adaptation might be less costly and mitigation even more challenging. Furthermore, costs for adaptation might be different during times of overshoot as compared to end of the century temperatures after having brought warming down to 1.5 °C.

Specific attention will be given to: (1) the incremental investment needs for mitigation (and potentially lower investment needs for adaptation) when going from 2 °C to 1.5 °C (e.g. (Bowen et al. 2014) for 2 °C mitigation and e.g.); (2) potential climate policy cost reductions through a coordinated response and spill overs to non-climate policy goals (McCollum et al. 2013); and (3) distributional implications (Luderer et al. 2016; Lüken et al. 2011).

Second, benefits of adaptation and mitigation will be synthesized separately from the cost assessment, abstaining deliberately from a quantification/monetization of all benefits and weighting against the costs (compare Stechow et al. (2016) for possible indicators). Interactions (complementarities/co-benefits and trade-offs - also qualitatively assessed where applicable) will be part of the benefit assessment as well.

Finally, there will be a stocktake on what the recent literature can tell about the costs of inaction and the implications of this (e.g. in terms of lock-in) for the achievement of the 1.5 °C target (Pfeiffer et al. 2016; Davis and Socolow 2014).

4.4.4.4 Macro-trends and interactions

Past IPCC reports have shown that the balance between costs and benefits of climate policies depends strongly upon the mix of policy instruments used to achieve GHG concentration targets (IPCC AR4, AR5). They also underline the need of policy flexibility across scale, location, time, sector and greenhouse gas.

AR5 indicated the total quantity of avoided emissions reductions required from non-OECD countries will need to be larger than that from the OECD over the rest of the 21st century, if the world is to meet a 450 ppmv CO_2-eq, given current global growth dynamics. Given diverse emission pathways, future regional and national temporal flexibility is important as delaying near-term mitigation can increase by several-fold, the economic costs of stabilizing at 450 ppmv CO_2-equivalent (IPCC, AR5). It also showed that the macroeconomic cost of mitigation increases substantially if key technological options are excluded or if the potential for emerging technologies is unrealised (e.g. BECCS).

The implications of these findings from AR5 on the implementation of the 1.5 °C target are strong. A 1.5 °C target provides for almost no temporal flexibility for ambitious climate policies in all world regions, unless the potential for transient or long-term overshoot is possible. Such an overshoot, would lead to consequent local and regional impact on threatened systems, extreme events and potential global impact, depending on the depth, length, spatial coverage and systemic coupling of such an overshoot.

Hence, 1.5 °C-centric climate policies will need to converge with structural changes in growth and sustainable development pathways, across most, if not all regions and sectors. This section, will therefore, examine three board questions: 1) barriers and enablers of near-term climate stabilisation to meet the 1.5 °C goal; 2) the economic and sustainable development policy implications of these policy measures and implementing instruments and institutions, including costs and benefits and 3) the ensemble of policy instruments, that may prove effective in effectively implementing these joined-up sustainable development, poverty reduction and climate mitigation and adaptation pathways.

Key themes to be addressed include:

1. Current macroeconomic trends including the risks of 'secular stagnation'. An assessment of short- and long-term prospects for the world economy; nature of the business regimes, income, consumption, savings and investment distribution; social security, pensions and ageing; export-led vs. endogenous growth and development strategies; role of economic, business and financial cycles.
2. Identification of how these trends can be an obstacle to:
   - triggering a low-carbon transition over the short-term with associated unemployment, adverse distributional effects, financial tensions, trade implications, loss of economic values due to divestment in emissions-intensive activities
   - low-carbon structural and technical changes over the medium- and long-run, including potential bifurcations and 'hysteresis' effects, discouragement of long run investments, crowding out effects and the risks of a decline in global productivity
3. Policy instruments (including carbon markets; legal and regulatory policies; fiscal, investment and financial tools, R&D and innovation) to overcome these barriers and use 1.5 °C compatible structural and technical changes, as levers to:
   - Secure the fulfilment of Sustainable Development, over the medium-term
   - Hedge against the risks of unstable, dualistic and exclusionary growth patterns in the current state of globalisation
   - Respond to short term concerns about unemployment, poverty and insecurity; trigger a long low-carbon growth cycle over the century
4. Assessment of relevant policy instruments and institutional arrangements to reinforce the NDCs to fulfil the Paris Agreement, based on regional and sectoral differentiation. This will include differential performance by development stage; vulnerability to economic, social and climate hazards.
5. Assessment of the investments needed to activate structural and technical changes and of their macroeconomic impact over the short- and medium-term. This would include a review of the proposed modification of financial intermediation systems to support this shift, including: impact on the capital flows, reduction of the gap between the propensity to save and invest, higher infrastructure investments and stimulation of short-term growth, and of inclusive and sustainable development over the long-run

4.5 Strengthening Implementation

4.5.1 Socio-economic

4.5.1.1 Introduction

In contrast to AR5 where the focus was on stabilization pathways targeting to limit global warming to less than 2 °C, the Paris Agreement has pronounced higher ambitions going to "well below" 2 °C with efforts to pursue 1.5 °C. In this section, the socio-economics implications are assessed in term of socio-economic impact of both mitigation and adaptation policies and measures, and also the socio-economic costs of inaction (i.e. failing to meet 2 °C).

The accumulation of greenhouse gases in the atmosphere is tightly correlated with the industrialisation and advance of the global economy, but this need not be the case. Central to this outcome is the idea that economic growth and gains in well-being can be decoupled from resource consumption and greenhouse gas emissions (Newman 2017). Literature is divided. The idea of "a-growth", as opposed to sustainable de-growth or growth, focuses on the policies and transactions that could drive the global economy while remaining within environmental limits (Van den Bergh 2011).

It is improbable that poor people in both developed and developing countries will support ambitious climate change targets or calls for behaviour change, unless these can simultaneously alleviate their burden of poverty, this will also true for other socio-economics groups. There is emerging evidence from African countries that low carbon climate resilient development pathways are not only more affordable, but also more accessible (Cartwright 2015; Hallegatte et al. 2016) (UNEP, 2011; Hallegatte et al., 2017). The Global Commission on the Economy and Climate (GCEC) confirmed that the transitions required to meet ambitious mitigation targets are capable, of not only delivering improved living standards and sustained economic growth, but also of saving money relative to more greenhouse gas intensive development pathways (Global Commission on the Economy and Climate (GCEC) 2014). Financial savings and efficiency improvement may cause the rebound effect, which can be mitigated with correct policies.

This finding, together with work that recognises the increasing interdependence and complexity of the global economy and environmental system, calls for new modes of economic analysis in order to allocate resources more effectively. In complex systems, the "whole cannot be fully understood by analysing its components" (Cilliers and Spurrett 1999).

Most models concur that early action in cutting emissions – reducing emissions by 2020 - holds economic advantages (ref needed). It is, however, inevitable that the economic shifts, including the reallocation of capital, required to limit warming to 1.5 °C will be significant and rapid (Jackson and Webster 2016). Understanding the structural shifts enables preparedness and the ability to cope with processes that otherwise seem disharmonious (Goldin and Kutarna 2016).

4.5.1.2 Economic impact and economic tools

Cost benefit analyses can be useful in prioritising climate change responses within constrained fiscal systems, but establishing 'benefit' as avoided climate risk is complicated by innate uncertainty and the limits of economic metrics such as GDP in capturing the full extent of climate damage (Cartwright et al. 2013). Linear modelling approaches risk assigning undue confidence in embedded assumptions. Assessing climate options through the exclusive lens of climate risk and vulnerability can limit the scope of the analysis (O'Brien et al. 2007)." The analytical challenge is to see rising greenhouse gas emissions as the by-product of inefficient economic systems that replicate poverty, trade imbalances and the two-way inter-connections between poverty and ecological degradation.

It is not the case that financial and manufactured capital are perfect substitutes for ecological capital, but metrics that compare the balance between the two can assist in charting more sustainable economic development pathways (Arrow et al. 2004).

Daron et al., (2014) and Ostrom (2009) concur that one of the core challenges in determining why some Socio-Ecological Systems are sustainable and others collapse is the identification and analyses of relationships at multiple levels and at different spatial and temporal scales. This has profound implications for the science of how best to respond to anthropogenic climate change.

4.5.1.3 Ethics, justice and values

AR5 is clear that mitigation and adaptation efforts raise issues of equity, justice and fairness, and analyses that ignore these dimensions can produce faulty policy prescripts.

Intergenerational welfare economics raises more questions than it is able to answer satisfactorily." (Dasgupta 2008, p. 167). Rights and justice, particularly those that are embedded in economic systems, are important for climate resilience in two ways: they have "intrinsic value" and therefore warrant inclusion in their own right, and they can "instrumental" in achieving climate goals (Ziervogel et al. 2017). The markets and policies that shape economic incentives and allocate capital offer the chance for a reconfiguration that could support an economic pathway leading to 1.5 °C, but this would require a major, coordinated, effort.

4.5.1.4 Social impact (employment, development, health, etc.) and acceptance including other non-economic impact (biodiversity, culture, values)

Evaluation of distributional impacts of actions and non-action: impact on LDCs and developed countries as well as sectoral implications, regional impacts and burden sharing.

Evaluation of co-benefits and risks: impact on GDP (mitigations cost will result in higher GDP?), energy security, local pollution (e.g. air pollution), migration, and risks (lock-in and technological disruptions, energy access, sustainability, and energy affordability, food vs energy trade off, socioeconomic and political disruptions).

Hallegate et al. (2016) call for making climate policies more "relevant" by embedding them in programmes that provide people with what they need and want, including food, mobility, energy and shelter. Seen through this lens, urban centres in developing countries that are characterised by rapid growth in consumption and population become important loci for climate action (Freire et al. 2014).

Critical is the interaction between policy tools (Section 4.5.4) and implementation and their implication for economic costs of stabilization at 1.5 °C, e.g. pre-existing distortions and market imperfections. Of equal importance are the links to the SDGs (is the combination of 1.5 °C and SDGs having a positive socio-economic impact, does 1.5 °C mean less adaptation? And if so what is the incremental benefit to mirror the incremental mitigation costs?)

4.5.2 Lifestyle and behavioural change (Linda, Paolo)

To mitigate anthropogenic climate change, substantial modification of a wide range of actions by many different people is needed. Such actions include the adoption of renewable resources (e.g., solar power), the implementation of resource efficiency measures in buildings (e.g., insulation, water saving devices), the adoption and use of sustainable innovations (e.g., electric vehicles) and resource-efficient appliances (e.g., energy-efficient domestic appliances), and changing user behaviour related to direct energy use (e.g., walk, cycle, or use public transport rather than drive; reduce room temperature) as well as embedded energy use, that is energy needed to produce, transport and dispose of products and services (e.g., reduce meat consumption or buy local seasonal food) (Steg 2016). Besides, other GHG could be reduced via changes in consumer behaviour (e.g., reduce methane emissions by reducing meat consumption).

Individual choices, preferences, and behaviour therefore have major implications for anthropogenic climate change and affect the ultimate effects of mitigation and adaptation strategies (Dietz et al. 2013; Hackmann et al. 2014; ISSC and UNESCO 2013; Sovacool 2014; Weaver et al. 2014; Vlek and Steg 2007). In fact, most if not all mitigation and adaptation strategies that aim to realise economic, physical or technological changes involve behaviour changes and require public support. Individuals need to accept proposed changes and policies, and use new technologies and infrastructure in the intended way. Hence, it is important to understand which factors promote changes in behaviour and lifestyles.

Promotion of required behaviour changes will be more likely when:

1. Behaviours are targeted with a substantial potential for carbon emission reduction or adaptation, thereby considering the plasticity of the behaviour (i.e., likelihood that the targeted behaviour will be adopted). Identify behavioural wedges (Dietz et al. 2009), and related time scales (i.e., immediate responses involving decreased use of goods and services versus responses in the long term such as replacement of technology). First target options with substantial potential for carbon emission reduction, such as adoption and use of sustainable technologies (Dietz et al. 2009). High potential as relatively low behavioural costs, and demonstrates that efforts are effective. Adopting such behaviour may strengthen environmental self-identity, which motivates people to act sustainably in subsequent situations in order to be consistent (Van der Werff et al. 2013). In the meanwhile, new technology, policy and institutions can be developed that promotes and facilitates further changes (further explained below). Not only consider adoption and use, but also political behaviour and behaviour in organisations that can advocate, support, or help block emission levels at various levels.

2. Behavioural change efforts will be more effective when they target important antecedents of behaviour. Therefore, it is important to identify factors influencing relevant behaviours, including individual as well as contextual factors.
   a. Individual factors include understanding of climate change, assessment of climate change risks, abilities (e.g., income, knowledge), and motivation to act in relevant mitigation and adaptation behaviours. Different types of motivations play a role, including cost-benefit considerations, environmental considerations, morality, affect, symbolic factors (e.g. identity, status), and group/social influence. Motivation can be intrinsic versus extrinsic – important to enhance intrinsic motivation so that people voluntarily engage in sustainable behaviour over and again. Decisions can be based on weighing costs and benefits, but more often are based on feelings or habit.
   b. Context may affect behaviour directly by defining cost and benefits of actions thereby defining opportunities people face, or indirectly by making people focus on particular consequences (Steg 2016). A wide range of contextual factors play a role, including economic factors, technology, spatial/infrastructural, institutional, and cultural.
3. Policy is implemented that targets important antecedents of behaviour and removes significant barriers to change. Policy can be aimed at rewarding or facilitating sustainable behaviour (carrots) or punishing or inhibiting undesired behaviour (sticks); change can be more or less voluntarily (e.g., via information) or imposed (e.g., by law). Many different strategies can be followed, targeting individual versus contextual factors. Understand psychological implications of such interventions, e.g. just providing information may not be effective, and pricing policies appear to be less effective than often assumed, and can even be counter effective, and nudges are not always effective. We will discuss literature and reviews revealing which strategies may be most effective and when, and which factors affect effects. Tailored approaches may be called far, taking into account individual and socio-cultural differences.
4. Policy and system changes require public and policy support, so it is important to understand which factors affect public support. We will review relevant factors, including perceived distributive and procedural fairness, trust, and factors discussed under and explain why support may increase after policy implementation (e.g., in trials). See also section 5.5.2.
5. Resulting behavioural and lifestyle changes should not threaten quality of life. Hence, it is important how engagement in adaptation and mitigation actions affects quality of life. We will introduce a broad conception of quality of life, including hedonic as well as eudemonic dimensions: life should be pleasurable, but also and particularly meaningful.

PM differences in required actions in LMICs and HICs. Notably, most research has been conducted in Western countries, far less in e.g. LMIC and former Soviet bloc countries. PM changing individuals vs groups (e.g. communities) vs organisations vs political systems.

4.5.3 Governance, institutions, capacity for change and politics

The implementation of sound responses and strategies for a 1.5 °C world will depend, amongst other factor, on reformed and strengthened governance structures. In some cases where it doesn't exist it needs to be formed and nurtured. Institutions play a key role within governance, as they are one of the enablers of governance structures. Institutions and the governance structures they are part of, need to have a holistic view. Considering climate change is a global problem, the principles of 'commons' might want to be explored as a way of sharing management and responsibilities (Chaffin et al. 2016; Ostrom et al. 1999; Young 2016).

Institutions need to interact with one another to share responsibilities ensuring that rules and regulations are followed (Ostrom et al. 1999). The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality, poverty alleviation, lead to a 1.5 °C world (mitigation) and enable the building of adaptive capacity (adaptation) and sustainable development. The proper streamlining of sustainable development and climate change goals within each institution mandate will be a step forward. There is existing literature showing how communities with strong governance structures are better able to adapt to extreme weather events and achieve sustainable development goals. These principles or schemes need to be analysed and see if they can be scaled up (see Section 4.2.2.3).

Capacity for change will have to occur at different scales: individual and household; within our own communities; in the workplace; in our politics; within our businesses. A multi-governance model for combining could combine simultaneous actions by global (i.e. UN), regional, national, subnational (e.g. state level) and local level (i.e. cities and municipalities) in a productive way. Solutions and change could come both from bottom-up approaches engaging citizens and local communities and from a top-down approach. A bottom-up approach will help the political scenarios where politicians have a short-term vision linked to the election cycles, whereas the 1.5 °C challenge needs long term planning and solutions.

Global governance models or supranational authorities can help guide transition periods between election cycles in order to ensure a medium and long-term vision is being considered and followed. An example of an area where this would be of use is to bridge the short-term vision of emergency response and disaster reconstruction with longer-term sustainable development goals. Very short-term disaster reconstruction programs and schedules can cause more harm if they are implemented hurriedly or aren't completed at all. However, these can be embedded within longer term sustainable development programs (short to medium term disaster reconstruction embedded within medium to long term sustainable development programs).

Further issues to be analysed:

- How to bring together these two divergent timeframes it is a big challenge.
- How can we embed capacity for change within our own communities? What factors influence capacity for change? Cross-cutting with Section 4.5.2.
- When we talk about politics, how do we keep politics separated from the main arguments?

[*Proposal for a Box with different governance frameworks suitable for 1.5 °C*]

4.5.4 Policy instruments (Sabine, Seth, Paolo, Mustafa, James)

4.5.4.1 Mitigation

In contrast to AR5 where the focus was on stabilization pathways targeting to limit global warming to less than 2°C, the Paris Agreement has pronounced higher ambitions going to "well below" 2 °C with efforts to pursue 1.5°C and thus this special report needs to assess the implications in terms of additional policy needs. A first impression of the involved magnitudes is given by a comparison of policy cost following the recommendations for analysis outlined in (Kriegler et al. 2014)..

A differentiation needs to be made between developed and less developed countries, where the mitigation burden on the latter has been higher in 2 °C pathways due to their higher baseline emissions due to ongoing population and GDP growth and higher mitigation potentials at a given carbon price. First research comparing 2 °C to 1.5 °C pathways indicates that this effect will be diminishing for less developed countries, in other words, the additional mitigation will to a large extent need to come from developed countries (Rogelj et al. 2015).

Furthermore, this section will use the special features of 1.5 °C pathways identified in Section 4.3.2.1 and build on the implications for sectors and regions assessed in Section 4.4 in order to determine gaps in implementation and match new knowledge on suitable policy instruments to this (even if this is distilled from literature not specific to 1.5 °C). This will also include measures that could potentially achieve mitigation and adaptation potentials.

The literature covered here will be on ex ante (e.g. Weigt et al. 2013) and ex post assessment of policy instruments (e.g. Calel and Dechezleprêtre 2014). The latter will especially help to identify and assess existing and potential barriers to implementation and distributional impact, including co-benefits of policies.

Note that the focus of this part of the implementation will be less on types of policy, but rather on the challenge to scale up the policy effort to achieve 1.5 °C given the timeframe, the institutional set-up, and the socioeconomic implications. In particular, we will investigate the necessary intensification, acceleration and additional adoption of traditional and innovative policies of different nature (regulatory, fiscal, financial, voluntary, and informative) at different levels (local, national, regional) and assessing policy packages targeting both mitigation and adaptation.

Finally, the Paris Agreement calls for strengthening the global response to climate change in the context of sustainable development, so mitigation and adaptation policies will be embedded into the broader context of the Sustainable Development Goals (SDGs). While Chapter 5 will focus specifically on the impact of implementation of mitigation and adaptation options on the SDGs, this section aims to identify new knowledge on policies that (a) focus on deep decarbonisation, and (b) are designed to exploit synergies between different policy goals (Jakob et al. 2016, 2015) and minimize adverse side effects.

4.5.4.2 Adaptation

4.5.4.2.1 Paris Agreement and strengthening adaptation implementation

The Paris Agreement takes a significant step forward in strengthening the adaptation pillar of global climate policy. By widening the normative framing around adaptation, calling for stronger adaptation commitments from states, being explicit about the multilevel nature of adaptation governance, and outlining stronger transparency mechanisms for assessing adaptation progress, the Agreement is a milestone for catalysing a global response on adaptation (Lesnikowski et al. 2016). Furthermore, by noting the importance of climate justice and the cultural significance of the environment the Agreement recognizes the diversity of existential significances attached to the environment across cultures. 1.5 °C poses a less substantial (although by no means insignificant) challenge to adaptation that higher warming trajectories, but strengthening implementation will require clarification of how the long-term goal for adaptation set out in Article 7 will be meaningfully realized (Lesnikowski et al. 2016; O'Neill et al. 2017). The challenge for Parties in implementing the Paris Agreement will be to establish credible commitments from state and non-state actors with regard to adaptation planning, implementation, and financing. Current INDCs outline proposed adaptation actions and provide a timeline for achieving these, yet sufficiency in-light of 1.5 °C and higher trajectories has been challenged, and will be compared to the special features of 1.5 °C pathways identified in Section 4.3.2.1 *[to integrate data from review of INDCs]*. Strengthening implementation in light of 1.5 °C requires procuring adequate financing to support adaptation efforts, political leadership, institutional governance, and a robust monitoring and evaluation framework (Lesnikowski et al. 2016; Magnan et al. 2015; Magnan and Ribera 2016) *[to integrate data from INDCs on funding committed]*.

4.5.4.2.2 Strengthening adaptation implementation at regional to local scales

Regional / national / local level action is required to compliment global commitments on adaptation. Studies examining the nature of the national response across nations reveal a picture of uneven progress, with adaptation leaders and laggards identified. Adaptation is primarily at the groundwork or planning stage, with substantially less progress on implementation. This section will examine specifically in the context of 1.5 °C pathways what the research says about how implementation of adaptation can be strengthened at regional to national levels, examine policy instruments available to achieve this (Henstra 2016), and include a text box(es) on cases of adaptation implementation (e.g. UK Climate Change Act and the adaptation reporting power (Jude et al. 2017).

4.5.5 Finance

Ambitious climate targets face the difficult problem of how to pay for the technologies, infrastructure and behaviour changes that will deliver the required transition. The World Economic Forum (2013) estimates that $85 trillion in investment (and reinvestment) in low carbon infrastructure is required by 2030 in order to comply with a 2 °C target. The Global Commission on the Economy and Climate (GCEC, 2014) has a higher estimate, $94 trillion, for the same target and period. Restricting emissions sufficiently to comply with a warming target of 1.5 °C will necessarily require a reallocation of capital that is more urgent than higher climate targets, but will also avoid economic damage; the shift away from fossil fuel based energy to alternative energy feedstocks and new energy consumption paradigms, including changes in life style, is central to this urgent investment transition. It is estimated that compliance with a 1.5 °C target and the SDGs would require investments of XXX USD.

Although passing from a 2 °C to a 1.5 °C demands and acceleration of action ($10 trillion in the "two to three years after 2018" following Wolf et al. (2017), it does not confront, as such macroeconomic constraints. Indeed, this would represent an increase of between around 2% to 3% of the total Gross Capital Formation[1] by comparison with a non-climate policy scenario and a drift of 0.5% to 0.8% of world GDP. These are significant shifts, but, as explained in Section 4.4.4., the world economy does not suffer from a lack of savings but from a gap of between the propensity to save and the propensity to invest that results in investments in real estates and land and in an excess of liquidities to absorb the saving glut (Arezki et al. 2016; Zenghelis 2012) (Summers 2015).

In this context there is some evidence that investing in the technologies and programmes that would deliver an ambitious climate goal could be cost saving (NCE 2016) or could cost less than initially imagined and may unlock new economic opportunities (Zenghelis 2012; Global Commission on the Economy and Climate (GCEC) 2014; Jaeger et al. 2015) (Aglietta et al 2015, Stern 2014) including in avoiding carbon intensive bifurcations in developing countries (Shukla 2010) and in the urban dynamics (Cartwright 2015).

The question then is how to achieve Article 2 of the Paris Agreement: "making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development". Three levels of constraints have to be considered:

- The amount of redirected investments: this amount is far higher than that the incremental investments (give figures) and all the more so that the up-front investment costs are between 1.9 to 3.2-fold higher than estimates relying on levelized costs (World Bank 2009, IEA 2014). Most of low carbon techniques are not end-of-pipe equipment. If the capital cost of a given quantity of clean energy is say 30% higher that a carbon based one that cost 100 the real redirection needs is 130. These investments encompass not only investment in the energy for which a lot of assessment in literature but also investments in infrastructure, material transformation and manufacturing sectors[2]. For example, the Cities Climate Finance Leadership Alliance notes that "…global demand for low-emission, climate-resilient urban infrastructure will be in the order of $4.5 trillion to $5.4 trillion annually from 2015 to 2030" (Cities Climate Finance Alliance 2015). The sectors concerned by this redirection represent about 40% of the gross capital formation.
- The fact that the risk-weighted capital costs are far higher that the capital costs in a certain environment because of the interplay between the intrinsic uncertainty of technologies at the mid-term of their learning-by-doing cycle and the uncertainty about the economic revenues of investing in low carbon techniques (regulatory uncertainty including about the level of carbon pricing policies, volatility of oil prices (Gross et al. 2010; Roques et al. 2008). This is an inhibiting factor for corporate companies under a 'shareholder business regime' (Pearl and Means 1932 and 'agency theories), for cities and local authorities, for SMEs with poor access to capital and for households (Hourcade 2017).
- The international transfers: the review of literature will have first to clarify the differences between a) transfers through cap and trade systems, including the CDM and b) transfers through financial mechanisms that reward upfront the low carbon investments and trigger combinations of public and private finance. Second, it will have to review existing assessments of such transfers worldwide and compare it with economic literature on the prospects of future world financial flows (primarily journals in 'international economics'. Third, it will have a specific focus on the short-term minimum commitment to providing the $100billion by 2020, required by the Green Climate Fund under Article 11 of the Paris Convention.
- Literature will then be mobilized to examine the 'state of the art' about the organisational changes needed to overcome the inertia due of existing behavioural routines and institutions.
- Reform of both supply and demand of finance so as to make low carbon and climate resilient projects and programmes more bankable. Review of financial devices apt to cut down the risk-weighted capital costs of the projects and increase the quantity of bankable projects for a given carbon price (Steckel 2016) (Hourcade et al., 2016).

[1] Compilation of the existing assessments (including OECD, IAE, UNFCCC) for 2 °C and the few forthcoming ones for 1.5 °C and conversion of these assessments into orders of magnitude of percent of increase of the Gross Capital Formation and of the GDP … at the World level here.

- Means of redirecting savings and the choices of institutional investors (pension funds, insurance companies) and of investment banks and development banks towards low carbon investments (carbon bond or any form of carbon based financial products). Role of disclosure rules (UNEP-Inquiry, G20), role of direct or indirect public guarantees, specific role of multilateral ‘Green Funds’, emergence of ‘low carbon assets’. In addition existing subsidies for fossil fuels create additional barriers for investments in low carbon technologies
- Role of new metrics that factor in the full social values of mitigation and adaptation activities to capital allocations, and counterbalance the role of existing financial risk metrics (Sirkis et al. 2015). This full social value, recognized by the article 108 of the Paris Agreement, encompasses the social cost of carbon (including climate uncertainty (Hallegatte 2009) and the development benefits of mitigation activities (Shukla and et al. 2017). This value, embedded in low carbon infrastructures, is a way of considered that a number of residents and governments, primarily but not solely in developing countries are unlikely to engage strong mitigation action solely for climate goals.
- Recognition of new asset classes including the low carbon assets and ecological assets that sequestrate carbon as a way of reshaping the individual and public choices. This class of assets is important to redirect financial flows worldwide and to compensate for the concerns about the assets that are ‘stranded’ by the divestment in carbon based activities and that back part of the assets of financial and insurance institutions. A specific case will have to be made about how this new class of assets can facilitate the low carbon transition in the fossil fuel producers. If no literature exists on this point we will have to make the link with the literature on ‘resources curse’ and the ‘optimal’ use of oil and gas rents.
- Allocated to the types of projects that will support the 1.5 °C target will require reform of both the supply and demand of international public and private finance, including the removal of all the subsidies for fossil fuels.
- Other points to be further analyzed:
    - The use of multiple climate models to ensure that capital allocations account for the innate climate uncertainty that is compounded by anthropogenic warming (Hallegatte 2009).
    - A new commitment to R&D of technologies and social behaviours consistent with 1.5 °C development pathways.

4.5.6 Technology transfer and innovation (Heleen, Marcos, Taishi, Seth)

Technology transfer and innovation are recognized as enablers of both mitigation and adaptation in the Paris Agreement, and well before that in the UNFCCC (UNFCCC 1992:Article 4.5). It is obvious that technology transfer and innovation can help adapting technologies to local circumstances, reduce costs, develop indigenous technology, and build capabilities globally (Ockwell et al. 2014). A 1.5 °C world is hard to imagine without a significant increase in global R&D expenditures, and development of innovation systems and associated capabilities around technologies for mitigation and adaptation in all countries (Coninck and Sagar, 2017, *forthcoming*).

The international institutional landscape around technology transfer and innovation includes the UNFCCC (via its technology framework and technology mechanism), the UN (a technology facilitation mechanism for the SDGs) and a huge variety of non-UN multilateral and bilateral cooperation initiatives, such as Mission Innovation (founded in 2015), the Consultative Group on International Agricultural Research (CGIAR, founded in the 1970s) and numerous initiatives of companies, foundations, governments and non-governmental and academic organisations. By far most technology transfer is happening driven by human needs and markets, in particular in areas with growing institutional and innovation capabilities (Glachant and Dechezleprêtre 2016), and the current landscape does leave gaps, in particular in least-developed countries, adaptation and innovation capabilities (de Coninck and Puig 2015). Literature suggests that the management or even monitoring of all these initiatives will fail to lead to better results; it is more cost-effective to ‘let a thousand flowers bloom’, while at the same time challenge and entice researchers in the public and the private sector to direct innovation towards low-carbon options (Haselip et al. 2015).

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2015: Article 10), which, among other things, should facilitate the undertaking and updating of technology needs assessments (TNAs), as well as the enhanced implementation of their results. An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a technology action plan (TAP) supports the new technology framework as well as Parties' long-term vision on technology development and transfer reflected in the Paris Agreement.

4.5.7 Integration and summary

4.6 Conclusions

References

Adger, W. N., 2016: Place, well-being, and fairness shape priorities for adaptation to climate change. *Glob. Environ. Chang.*, **38**, A1–A3, doi:10.1016/j.gloenvcha.2016.03.009.

Adger, W. N., and Coauthors, 2007: Assessment of adaptation practices, options, constraints and capacity. *Climate Change 2007: Working Group III: Mitigation of Climate Change*, 717–744.

Ågren, G. I., 2000: Temperature dependence of old soil organic matter. *AMBIO A J. Hum. Environ.*, **29**, 55–55, doi:10.1579/0044-7447-29.1.55.

Åhman, M., L. J. Nilsson, and B. Johansson, 2016: Global climate policy and deep decarbonization of energy-intensive industries. *Clim. Policy*, **0**, 1–16, doi:10.1080/14693062.2016.1167009.

Ahmed, S., and E. Fajber, 2009: Engendering adaptation to climate variability in Gujarat, India. *Gend. Dev.*, **17**, 33–50, doi:10.1080/13552070802696896.

Akbari, H., H. Damon Matthews, and D. Seto, 2012: The long-term effect of increasing the albedo of urban areas. *Environ. Res. Lett.*, **7**, 24004, doi:10.1088/1748-9326/7/2/024004.

Alstone, P., D. Gershenson, and D. M. Kammen, 2015: Decentralized energy systems for clean electricity access. *Nat. Clim. Chang.*, **5**, 305–314, doi:10.1038/nclimate2512.

Angel, R., 2006: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Natl. Acad. Sci. U. S. A.*, **103**, 17184–17189, doi:10.1073/pnas.0608163103. http://www.ncbi.nlm.nih.gov/pubmed/17085589 (Accessed April 8, 2017).

Araújo, K., 2014: The emerging field of energy transitions: Progress, challenges, and opportunities. *Energy Res. Soc. Sci.*, **1**, 112–121, doi:10.1016/j.erss.2014.03.002.

Archibald, S., and G. P. Hempson, 2016: Competing consumers: contrasting the patterns and impacts of fire and mammalian herbivory in Africa. *Phil. Trans. R. Soc. B*, **371**, 20150309.

Arezki, R., P. Bolton, S. Peters, F. Samama, and J. E. Stiglitz, 2016: *From global savings glut to financing infrastructure: the advent of investment platforms*.

Arrow, K., and Coauthors, 2004: Are we consuming too much? *J. Econ. Perspect.*, **18**, 147–172.

Auffhammer, M., and E. . Mansur, 2014: Measuring climatic impacts on energy consumption: A review of the empirical literature. *Energy Econ.*, **46**, 522–530, doi:10.1016/j.eneco.2014.04.017.

Bahadur, A., and T. Tanner, 2014: Transformational resilience thinking: putting people, power and politics at the heart of urban climate resilience. *Environ. Urban.*, **26**, 1–15, doi:10.1177/0956247814522154.

Baker-Shelley, A., A. van Zeijl-Rozema, and P. Martens, 2017: A Conceptual Synthesis of Organisational Transformation: How to Navigate Pathways to Sustainability at Universities? *J. Clean. Prod.*, **145**, 262–276, doi:10.1016/j.jclepro.2017.01.026.

Barnett, J., L. S. Evans, C. Gross, A. S. Kiem, R. T. Kingsford, J. P. Palutikof, C. M. Pickering, and S. G. Smithers, 2015: From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecol. Soc.*, **20**, doi:10.5751/ES-07698-200305.

Bazilian, M., S. Nakhooda, and T. Van De Graaf, 2014: Energy governance and poverty. *Energy Res. Soc. Sci.*, **1**, 217–225, doi:10.1016/j.erss.2014.03.006. http://dx.doi.org/10.1016/j.erss.2014.03.006.

Belz, F.-M., 2004: A transition towards sustainability in the Swiss agri-food chain (1970--2000): using and improving the multi-level perspective. *Syst. Innov. Transit. to Sustain.*, 97–114.

Berkhout, F., 2002: Technological regimes, path dependency and the environment. *Glob. Environ. Chang.*, **12**, 1–4.

Bidgoli, H., 2010: *The Handbook of Technology Management, Supply Chain Management, Marketing and Advertising, and Global Management*. John Wiley & Sons,.

Biesbroek, G. R., J. E. M. Klostermann, C. J. A. M. Termeer, and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Reg. Environ. Chang.*, **13**, 1119–1129, doi:10.1007/s10113-013-0421-y.

Bosetti, V., C. Carraro, E. Massetti, A. Sgobbi, and M. Tavoni, 2009: Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations. *Resour. Energy Econ.*, **31**, 123–137, doi:10.1016/j.reseneeco.2009.01.001.

Bosetti, V., C. Carraro, and M. Tavoni, 2009: Climate Change Mitigation Strategies in Fast- Growing Countries : The Benefits of Early Action Climate Change. *Energy Econ.*, **31**. http://hdl.handle.net/10419/30551.

Bosetti, V., C. Carraro, and M. Tavoni, 2009: A Chinese commitment to commit: Can it break the negotiation stall? *Clim. Change*, **97**, 297–303, doi:10.1007/s10584-009-9726-8.

Bowen, A., E. Campliglio, and M. Tavoni, 2014: a Macroeconomic Perspective on Climate Change Mitigation: Meeting the Financing Challenge. *Clim. Chang. Econ.*, **5**, 1440005, doi:10.1142/S2010007814400053. http://www.worldscientific.com/doi/abs/10.1142/S2010007814400053.

Burnham, M., Z. Ma, and B. Zhang, 2015: Making sense of climate change: Hybrid epistemologies, socio-natural assemblages and smallholder knowledge. *Area*, **48**, 18–26, doi:10.1111/area.12150.

Burt, A., B. Hughes, and G. Milante, 2014: *Eradicating Poverty in Fragile States: Prospects of Reaching The "High-Hanging" Fruit by 2030*. Washington D.C.,.

Calel, R., and A. Dechezleprêtre, 2014: Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Rev. Econ. Stat.*, **98**, 173–191, doi:10.1162/REST_a_00470.

http://dx.doi.org/10.1162/REST_a_00470.
Calvin, K., M. Wise, D. Klein, D. McCollum, M. Tavoni, B. van der ZWAAN, and D. P. van Vuuren, 2013: A Multi-model Analysis Of The Regional and Sectoral Roles Of Bioenergy In Near- And Long-term CO2 Emissions Reduction. *Clim. Chang. Econ.*, **4**, 1340014, doi:10.1142/S2010007813400149. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400149.
Campagnolo, L., C. Carraro, M. Davide, F. Eboli, E. Lanzi, and R. Parrado, 2016: Can climate policy enhance sustainability? *Clim. Change*, **137**, 639–653, doi:10.1007/s10584-016-1701-6.
Campagnolo, L., and M. Davide, 2015: Can Paris deal boost SDGs achievement ? An assessment of climate-sustainability co-benefits or side-effects. 1–16.
Cartwright, A., 2015: *Better growth, better cities: reimagining and rethinking urbanisation in Africa*.
Cartwright, A., J. Blignaut, M. De Wit, K. Goldberg, M. Mander, S. O'Donoghue, and D. Roberts, 2013: Economics of climate change adaptation at the local scale under conditions of uncertainty and resource constraints: the case of Durban, South Africa. *Environ. Urban.*, **25**, 139–156, doi:10.1177/0956247813477814. http://journals.sagepub.com/doi/10.1177/0956247813477814 (Accessed April 9, 2017).
Chaffin, B. C., H. Gosnell, and B. A. Cosens, 2014: A Decade of Adaptive Governance Scholarship: Synthesis and Future Directions. **19**, 56. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2717757 (Accessed April 9, 2017).
Challinor, A. J., J. Watson, D. B. Lobell, S. M. Howden, D. R. Smith, and N. Chhetri, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Chang.*, **4**, 287–291.
Chaturvedi, V., and Coauthors, 2014: Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Clim. Change*, **123**, 597–609, doi:10.1007/s10584-013-0898-x.
Cilliers, P., and D. Spurrett, 1999: Complexity and post-modernism: Understanding complex systems. *South African J. Philos.*, **18**, 258–274.
Cities Climate Finance Alliance, 2015: *The State of City Climate Finance*. http://hdl.handle.net/20.500.11822/7523.
Clarke, L., and Coauthors, 2014: Assessing transformation pathways. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* , T.Z. and J.C.M. (eds. . Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, Ed., Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA http://pure.iiasa.ac.at/11119/ (Accessed April 6, 2017).
Clarke, L. E., A. A. Fawcett, J. P. Weyant, J. McFarland, V. Chaturvedi, and Y. Zhou, 2004: Technology and US emissions reductions goals: Results of the EMF 24 modelling exercise. *Energy J.*,.
Clarke, L., V. Krey, J. Weyant, and V. Chaturvedi, 2012: Regional energy system variation in global models: Results from the Asian Modeling Exercise scenarios. *Energy Econ.*, **34**, doi:10.1016/j.eneco.2012.07.018.
Connolly, D., and B. V. Mathiesen, 2014: A technical and economic analysis of one potential pathway to a 100% renewable energy system. *Int. J. Sustain. Energy Plan. Manag.*, **1**, 7–28, doi:10.5278/ijsepm.2014.1.2.
Cosbey, A., and R. Tarasofsky, 2007: *Climate Change, Competitiveness and Trade*. Chatham House, London,.
Cote, M., and A. J. Nightingale, 2012: Resilience thinking meets social theory. *Prog. Hum. Geogr.*, **36**, 475–489, doi:10.1177/0309132511425708. http://journals.sagepub.com/doi/10.1177/0309132511425708 (Accessed April 9, 2017).
Crassous, R., P. Criqui, J. C. Hourcade, and S. Mathy, 2008: *Carbon Constrained Scenarios: what stake for heavy industry?*
Crutzen, P. J., 2006: Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? *Clim. Change*, **77**, 211–220, doi:10.1007/s10584-006-9101-y. http://link.springer.com/10.1007/s10584-006-9101-y (Accessed April 8, 2017).
Cullen, J. M., J. M. Allwood, and M. D. Bambach, 2012: Mapping the global flow of steel: From steelmaking to end-use goods. *Environ. Sci. Technol.*, **46**, 13048–13055, doi:10.1021/es302433p.
DaMatta, F. M., A. Grandis, B. C. Arenque, and M. S. Buckeridge, 2010: Impacts of climate changes on crop physiology and food quality. *Food Res. Int.*, **43**, 1814–1823, doi:10.1016/j.foodres.2009.11.001. http://www.sciencedirect.com/science/article/pii/S0963996909003421 (Accessed April 9, 2017).
Daron, J. D., K. Sutherland, C. Jack, and B. C. Hewitson, 2015: The role of regional climate projections in managing complex socio-ecological systems. *Reg. Environ. Chang.*, **15**, 1–12. http://link.springer.com/article/10.1007/s10113-014-0631-y (Accessed April 8, 2017).
Dasgupta, P., 2008: Discounting climate change. *J. Risk Uncertain.*, **37**, 141–169, doi:10.1007/s11166-008-9049-6. http://link.springer.com/article/10.1007/s11166-008-9049-6 (Accessed January 30, 2013).
Davidson, E. A., and Coauthors, 2006: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165–173, doi:10.1038/nature04514. http://www.ncbi.nlm.nih.gov/pubmed/16525463.
Davidson, P., C. Burgoyne, H. Hunt, and M. Causier, 2012: Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems. *Philos. Trans. R. Soc. London A Math. Phys. Eng. Sci.*, **370**.

http://rsta.royalsocietypublishing.org/content/370/1974/4263 (Accessed April 8, 2017).

Davis, S. J., and R. H. Socolow, 2014: Commitment accounting of CO2 emissions. *Environ. Res. Lett.*, **9**, 84018, doi:10.1088/1748-9326/9/8/084018. http://stacks.iop.org/1748-9326/9/i=8/a=084018.

de Coninck, H., and D. Puig, 2015: Assessing climate change mitigation technology interventions by international institutions. *Clim. Change*, **131**, 417–433, doi:10.1007/s10584-015-1344-z. http://www.scopus.com/inward/record.url?eid=2-s2.0-84937515750&partnerID=tZOtx3y1.

De Souza, A. P., B. C. Arenque, E. Q. P. Tavares, and M. S. Buckeridge, 2016: Transcriptomics and Genetics Associated with Plant Responses to Elevated CO2 Atmospheric Concentrations. *Plant Genomics and Climate Change*, Springer, 67–83.

De Souza, A. P., J.-C. Cocuron, A. C. Garcia, A. P. Alonso, and M. S. Buckeridge, 2015: Changes in Whole-Plant Metabolism during the Grain-Filling Stage in Sorghum Grown under Elevated CO2 and Drought. *Plant Physiol.*, **169**, 1755–1765, doi:10.1104/pp.15.01054.

den Elzen, M., P. Lucas, and D. van Vuuren, 2005: Abatement costs of post-Kyoto climate regimes. *Energy Policy*, **33**, 2138–2151, doi:10.1016/j.enpol.2004.04.012.

Denton, F., T. Wilbanks, and A. Abeysinghe, 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. *Climate Change 2014 Impacts, Adaptation, and Vulnerability*, 1101–1131 https://wg2ar5gate.wordpress.com/chapter-20/ (Accessed April 8, 2017).

Di Leo, S., F. Pietrapertosa, S. Loperte, M. Salvia, and C. Cosmi, 2015: Energy systems modelling to support key strategic decisions in energy and climate change at regional scale. *Renew. Sustain. Energy Rev.*, **42**, 394–414, doi:10.1016/j.rser.2014.10.031. http://www.sciencedirect.com/science/article/pii/S136403211400848X (Accessed April 6, 2017).

Dietz, T., G. T. Gardner, J. Gilligan, P. C. Stern, and M. P. Vandenbergh, 2009: Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proc. Natl. Acad. Sci.*, **106**, 18452–18456, doi:10.1073/pnas.0908738106. http://www.pnas.org/content/106/44/18452.abstract.

Dietz, T., P. C. Stern, and E. U. Weber, 2013: Reducing Carbon-Based Energy Consumption through Changes in Household Behavior. *Daedalus*, **142**, 78–89, doi:10.1162/DAED_a_00186. http://dx.doi.org/10.1162/DAED_a_00186.

Döll, P., H. Hoffmann-Dobrev, F. T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B. R. Scanlon, 2012: Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.*, **59**–**60**, 143–156, doi:http://doi.org/10.1016/j.jog.2011.05.001. http://www.sciencedirect.com/science/article/pii/S0264370711000597.

Dowling, R., P. McGuirk, and H. Bulkeley, 2014: Retrofitting cities: Local governance in Sydney, Australia. *Cities*, **38**, 18–24, doi:10.1016/j.cities.2013.12.004.

Droste, N., and Coauthors, 2016: Steering innovations towards a green economy: Understanding government intervention. *J. Clean. Prod.*, **135**, 426–434, doi:10.1016/j.jclepro.2016.06.123. http://www.sciencedirect.com/science/article/pii/S0959652616308009 (Accessed April 12, 2017).

Dykema, J. A., D. W. Keith, and F. N. Keutsch, 2016: Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophys. Res. Lett.*, **43**, 7758–7766, doi:10.1002/2016GL069258. http://doi.wiley.com/10.1002/2016GL069258 (Accessed April 8, 2017).

Ebi, K. L., and Coauthors, 2014: A new scenario framework for climate change research: Background, process, and future directions. *Clim. Change*, **122**, 363–372, doi:10.1007/s10584-013-0912-3.

Effiong, U., and R. L. Neitzel, 2016: Assessing the direct occupational and public health impacts of solar radiation management with stratospheric aerosols. *Environ. Health*, **15**, 7, doi:10.1186/s12940-016-0089-0. http://www.ncbi.nlm.nih.gov/pubmed/26786592 (Accessed April 8, 2017).

Ekholm, T., and H. Korhonen, 2016: Climate change mitigation strategy under an uncertain Solar Radiation Management possibility. *Clim. Change*, **139**, 503–515, doi:10.1007/s10584-016-1828-5. http://link.springer.com/article/10.1007/s10584-016-1828-5 (Accessed April 8, 2017).

Ensor, J. E., S. Park, S. Attwood, A. M. Kaminski, and J. E. Johnson, 2016: Can community-based adaptation increase resilience? *Clim. Dev.*, 1–18, doi:10.1080/17565529.2016.1223595. http://www.tandfonline.com/doi/abs/10.1080/17565529.2016.1223595 (Accessed April 8, 2017).

Eriksen, S., and Coauthors, 2011: When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Clim. Dev.*, **3**, 7–20, doi:10.3763/cdev.2010.0060.

Etzion, D., J. Gehman, F. Ferraro, and M. Avidan, 2017: Unleashing sustainability transformations through robust action. *J. Clean. Prod.*, **140**, 167–178, doi:10.1016/j.jclepro.2015.06.064. http://www.sciencedirect.com/science/article/pii/S0959652615007945 (Accessed April 8, 2017).

Fawcett, A. A., and Coauthors, 2015: Can Paris pledges avert severe climate change? *Science (80-.).*, **350**, 1168–1169.

Field, C. B., and Coauthors, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change.

Fink, J. H., 2013: Geoengineering cities to stabilise climate. *Proc. Inst. Civ. Eng. - Eng. Sustain.*, **166**, 242–248, doi:10.1680/ensu.13.00002. http://www.icevirtuallibrary.com/doi/10.1680/ensu.13.00002 (Accessed April 6,

2017).
Fischedick, M., and Coauthors, 2014: Industry. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 739–810.
Flannery, T., 2015: *Atmosphere of hope: Searching for solutions to the climate crisis*. Penguin Books Limited, London, UK,.
Forsyth, T., 2013: Community-based adaptation: a review of past and future challenges. *Wiley Interdiscip. Rev. Clim. Chang.*, **4**, 439–446, doi:10.1002/wcc.231. http://doi.wiley.com/10.1002/wcc.231 (Accessed April 8, 2017).
Fouquet, R., 2016: Lessons from energy history for climate policy: Technological change, demand and economic development. *Energy Res. Soc. Sci.*, **22**, 79–93, doi:10.1016/j.erss.2016.09.001. http://www.sciencedirect.com/science/article/pii/S2214629616302080 (Accessed April 6, 2017).
Francesch-Huidobro, M., 2015: Collaborative governance and environmental authority for adaptive flood risk: Recreating sustainable coastal cities: Theme 3: Pathways towards urban modes that support regenerative sustainability. *J. Clean. Prod.*, **107**, 568–580, doi:10.1016/j.jclepro.2015.05.045. http://www.sciencedirect.com/science/article/pii/S0959652615005922 (Accessed April 6, 2017).
Freire, M., S. Lall, and D. Leipziger, 2014: *Africa's urbanization: challenges and opportunities*. Washington D.C.,.
Fricko, O., S. Parkinson, N. Johnson, M. Strubegger, T. H. M. Van Vliet, and K. Riahi, 2016: Energy sector water use implications of a 2 degree climate policy. *Environ. Res. Lett.*, **11**, 34011, doi:10.1088/1748-9326/11/3/034011. http://iopscience.iop.org/article/10.1088/1748-9326/11/3/034011/meta (Accessed April 8, 2017).
Fujimori, S., M. Kainuma, T. Masui, T. Hasegawa, and H. Dai, 2014: The effectiveness of energy service demand reduction: A scenario analysis of global climate change mitigation. *Energy Policy*, **75**, 379–391, doi:10.1016/j.enpol.2014.09.015.
Gaffney, O., and W. Steffen, 2017: The Anthropocene equation. *Anthr. Rev.*, 205301961668802, doi:10.1177/2053019616688022. http://journals.sagepub.com/doi/10.1177/2053019616688022.
Geels, F. W., 2004: From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Res. Policy*, **33**, 897–920, doi:10.1016/j.respol.2004.01.015. http://linkinghub.elsevier.com/retrieve/pii/S0048733304000496 (Accessed April 8, 2017).
Geels, F. W., F. Kern, G. Fuchs, N. Hinderer, G. Kungl, J. Mylan, M. Neukirch, and S. Wassermann, 2016: The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014). *Res. Policy*, **45**, 896–913, doi:10.1016/j.respol.2016.01.015. http://www.sciencedirect.com/science/article/pii/S0048733316300087 (Accessed April 7, 2017).
Geels, F. W., and J. Schot, 2007: Typology of sociotechnical transition pathways. *Res. Policy*, **36**, 399–417, doi:10.1016/j.respol.2007.01.003.
Gerbens-Leenes, P. W., A. R. van Lienden, A. Y. Hoekstra, and T. H. van der Meer, 2012: Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030. *Glob. Environ. Chang.*, **22**, 764–775, doi:10.1016/j.gloenvcha.2012.04.001. http://www.sciencedirect.com/science/article/pii/S0959378012000489 (Accessed April 8, 2017).
Gerbens-Leenes, W., A. Y. Hoekstra, and T. H. van der Meer, 2009: The water footprint of bioenergy. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 10219–10223, doi:10.1073/pnas.0812619106.
Glachant, M., and A. Dechezleprêtre, 2016: What role for climate negotiations on technology transfer? *Clim. Policy*, **0**, 1–15, doi:10.1080/14693062.2016.1222257. http://dx.doi.org/10.1080/14693062.2016.1222257.
Global Commission on the Economy and Climate (GCEC), 2014: *Better growth, better climate: The new climate economy report*. http://newclimateeconomy.report/2014/wp-content/uploads/2014/08/NCE-Global-Report_web.pdf.
Goldin, I., and C. Kutarna, 2016: *Age of Discovery: Navigating the Risks and Rewards of Our New Renaissance*. Bloomsbury Publishing,.
Gregersen, C., and Coauthors, 2016: Implementation of the 2030 Agenda in the European Union : Constructing an EU approach to Policy Coherence for Sustainable Development for Sustainable Development.
Gross, R., W. Blyth, and P. Heptonstall, 2010: Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. *Energy Econ.*, **32**, 796–804.
Grothmanna, T., and A. Patt, 2005: Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Glob. Environ. Chang.*, **15**, 199–213.
Gupta, J., and Coauthors, 2015: Sustainable Development Goals and Inclusive Development.
Haberl, H., 2015: Competition for land: A sociometabolic perspective. *Ecol. Econ.*, **119**, 424–431, doi:http://doi.org/10.1016/j.ecolecon.2014.10.002. http://www.sciencedirect.com/science/article/pii/S0921800914003127.
Hackmann, H., S. C. Moser, and A. L. St. Clair, 2014: The social heart of global environmental change. *Nat. Clim. Chang.*, **4**, 653–655. http://dx.doi.org/10.1038/nclimate2320.
Haines, A., and Coauthors, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet*, doi:10.1016/S0140-6736(09)61759-1.

Halbe, J., 2017: Governance of Transformations towards Sustainable Water, Food and Energy Supply Systems-Facilitating Sustainability Innovations through Multi-Level Learning. https://repositorium.uni-osnabrueck.de/handle/urn:nbn:de:gbv:700-2017022715609 (Accessed April 8, 2017).
Hale, T., 2016: " All Hands on Deck " : The Paris Agreement and Nonstate Climate Action. 12–22, doi:10.1162/GLEP.
Hallegatte, S., 2015: The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience. *Policy Res. Work. Pap.*, 1–40. https://www.gfdrr.org/sites/gfdrr.org/files/documents/Public finance and macroeconomics, Paper 3.pdf (Accessed April 8, 2017).
Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Glob. Environ. Chang.*, **19**, 240–247, doi:10.1016/j.gloenvcha.2008.12.003. http://www.sciencedirect.com/science/article/pii/S0959378008001192 (Accessed April 8, 2017).
Hallegatte, S., K. J. Mach, and others, 2016: Make climate-change assessments more relevant. *Nature*, **534**, 613–615.
Hanasaki, N., and Coauthors, 2013: A global water scarcity assessment under Shared Socio-economic Pathways - Part 1: Water use. *Hydrol. Earth Syst. Sci.*, **17**, 2375–2391, doi:10.5194/hess-17-2375-2013.
Harding, A., and J. B. Moreno-Cruz, 2016: Solar geoengineering economics: From incredible to inevitable and half-way back. *Earth's Futur.*, **4**, 569–577, doi:10.1002/2016EF000462. http://doi.wiley.com/10.1002/2016EF000462 (Accessed April 8, 2017).
Haselip, J., U. E. Hansen, D. Puig, S. Trærup, and S. Dhar, 2015: Governance, enabling frameworks and policies for the transfer and diffusion of low carbon and climate adaptation technologies in developing countries. *Clim. Change*, **131**, 363–370, doi:10.1007/s10584-015-1440-0.
He, C., and Coauthors, 2016: National and subnational all-cause and cause-specific child mortality in China, 1996-2015: a systematic analysis with implications for the Sustainable Development Goals. 30334–30335, doi:10.1016/S2214-109X(16)30334-5. www.thelancet.com/lancetgh%0Ahttp://dx.doi.org/10.1016/.
Henderson, B. B., P. J. Gerber, T. E. Hilinski, A. Falcucci, D. S. Ojima, M. Salvatore, and R. T. Conant, 2015: Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agric. Ecosyst. Environ.*, **207**, 91–100, doi:10.1016/j.agee.2015.03.029. http://www.sciencedirect.com/science/article/pii/S0167880915001139 (Accessed April 9, 2017).
Henstra, D., 2016: The tools of climate adaptation policy: analysing instruments and instrument selection. *Clim. Policy*, **16**, 496–521, doi:10.1080/14693062.2015.1015946. http://dx.doi.org/10.1080/14693062.2015.1015946.
Hernandez, R. R., and Coauthors, 2014: Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.*, **29**, 766–779, doi:10.1016/j.rser.2013.08.041.
Hinkel, J., and Coauthors, 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3292–3297, doi:10.1073/pnas.1222469111. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3948227&tool=pmcentrez&rendertype=abstract.
Högy, P., H. Wieser, P. Köhler, K. Schwadorf, J. Breuer, J. Franzaring, R. Muntifering, and A. Fangmeier, 2009: Effects of elevated CO2 on grain yield and quality of wheat: results from a 3-year free-air CO 2 enrichment experiment. *Plant Biol.*, **11**, 60–69, doi:10.1111/j.1438-8677.2009.00230.x. http://doi.wiley.com/10.1111/j.1438-8677.2009.00230.x (Accessed April 9, 2017).
Hook, M., J. Li, N. Oba, and S. Snowden, 2011: Descriptive and Predictive Growth Curves in Energy System Analysis. *Nat. Resour. Res.*, **20**, 103–116, doi:10.1007/s11053-011-9139-z.
Hrelja, R., M. Hjerpe, and S. Storbjoerk, 2015: Creating Transformative Force? The Role of Spatial Planning in Climate Change Transitions Towards Sustainable Transportation. *J. Environ. Policy Plan.*, **17**, 617–635, doi:10.1080/1523908X.2014.1003535. http://www.tandfonline.com/doi/full/10.1080/1523908X.2014.1003535 (Accessed April 6, 2017).
Humpenöder, F., and Coauthors, 2015: Land-use and carbon cycle responses to moderate climate change: Implications for land-based mitigation? *Environ. Sci. Technol.*, **49**, 6731–6739, doi:10.1021/es506201r. http://pubs.acs.org/doi/abs/10.1021/es506201r (Accessed April 6, 2017).
Inderberg, T. H., S. Eriksen, K. O'Brien, and L. Sygna, 2014: *Climate change adaptation and development: transforming paradigms and practices*. Routledge,.
IPCC, 2014: *Climate Change 2014 Synthesis Report*. Intergovernmental Panel on Climate Change,.
IPCC, 2016: *IPCC SR1.5 scoping document*. Bangkok, Thailand, 17-20 pp. http://www.ipcc.ch/apps/eventmanager/documents/40/210920161009-Doc.11-Outline1.5.pdf.
Irvine, P. J., and Coauthors, 2017: Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Futur.*, **5**, 93–106, doi:10.1002/2016EF000389.
Irvine, P. J., B. Kravitz, M. G. Lawrence, and H. Muri, 2016: An overview of the Earth system science of solar geoengineering. *Wiley Interdiscip. Rev. Clim. Chang.*, **7**, 815–833, doi:10.1002/wcc.423.
Irvine, P. J., A. Ridgwell, and D. J. Lunt, 2011: Climatic effects of surface albedo geoengineering. *J. Geophys. Res. Atmos.*, **116**, n/a-n/a, doi:10.1029/2011JD016281.
Isley, S. C., R. J. Lempert, S. W. Popper, and R. Vardavas, 2015: The effect of near-term policy choices on long-term greenhouse gas transformation pathways. *Glob. Environ. Chang.*, **34**, 147–158, doi:10.1016/j.gloenvcha.2015.06.008. http://www.sciencedirect.com/science/article/pii/S0959378015300029

(Accessed April 7, 2017).
ISSC, UNESCO, and ISSC - UNESCO, 2013: *World Social Science Report 2013: Changing Global Environments*. Paris, 250-254 pp. http://www.unesco.org/new/en/social-and-human-sciences/resources/reports/world-social-science-report-2013/.
Izrael, Y. A., E. M. Volodin, S. V. Kostrykin, A. P. Revokatova, and A. G. Ryaboshapko, 2014: The ability of stratospheric climate engineering in stabilizing global mean temperatures and an assessment of possible side effects. *Atmos. Sci. Lett.*, **15**, 140–148, doi:10.1002/asl2.481.
Jackson, L. S., J. A. Crook, and P. M. Forster, 2016: An intensified hydrological cycle in the simulation of geoengineering by cirrus cloud thinning using ice crystal fall speed changes. *J. Geophys. Res. Atmos.*, **121**, 6822–6840, doi:10.1002/2015JD024304.
Jackson, T., and R. Webster, 2016: *Limits Revisited: A review of the limits to growth debate*. http://limits2growth.org.uk/wp-content/uploads/2016/04/Jackson-and-Webster-2016-Limits-Revisited.pdf.
Jacobson, M. Z., and J. E. Ten Hoeve, 2012: Effects of urban surfaces and white roofs on global and regional climate. *J. Clim.*, **25**, 1028–1044, doi:10.1175/JCLI-D-11-00032.1.
Jaeger, C. C., F. Schütze, S. Fürst, D. Mangalagiu, F. Meißner, J. Mielke, G. A. Steudle, and S. Wolf, 2015: Investment-Oriented Climate Policy—An Opportunity for Europe. *Global Climate Forum: Berlin, Germany*.
Jakob, M., C. Chen, S. Fuss, A. Marxen, and O. Edenhofer, 2015: Development incentives for fossil fuel subsidy reform. *Nat. Clim. Chang.*, **5**, 709–712. http://dx.doi.org/10.1038/nclimate2679.
Jakob, M., C. Chen, S. Fuss, A. Marxen, N. D. Rao, and O. Edenhofer, 2016: Carbon Pricing Revenues Could Close Infrastructure Access Gaps. *World Dev.*, **84**, 254–265, doi:10.1016/j.worlddev.2016.03.001. http://www.sciencedirect.com/science/article/pii/S0305750X16000425 (Accessed April 4, 2017).
Jensen, J. S., C. F. Fratini, and M. A. Cashmore, 2015: Socio-technical Systems as Place-specific Matters of Concern: The Role of Urban Governance in the Transition of the Wastewater System in Denmark. *J. Environ. Policy Plan.*, **18**, 234–252, doi:10.1080/1523908X.2015.1074062. http://www.tandfonline.com/doi/full/10.1080/1523908X.2015.1074062 (Accessed April 7, 2017).
Jiang, L., and B. C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 193–199, doi:10.1016/j.gloenvcha.2015.03.008. http://www.sciencedirect.com/science/article/pii/S0959378015000394 (Accessed April 8, 2017).
Johansson, D. J. A. et al, 2012: Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime. *Mitig. Adapt. Strateg. Glob. Chang.*,. http://hdl.handle.net/10419/67337.
Jones, A., and Coauthors, 2013: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 9743–9752, doi:10.1002/jgrd.50762.
Jones, L., and E. Boyd, 2011: Exploring social barriers to adaptation: Insights from Western Nepal. *Glob. Environ. Chang.*, **21**, 1262–1274, doi:10.1016/j.gloenvcha.2011.06.002.
Jonker, W., A. C. Brent, J. K. Musango, and I. de Kock, 2017: Implications of biofuel production in the Western Cape province, South Africa: A system dynamics modelling approach of South Africa: A system dynamics modelling approach. *J. Energy South. Africa*, **28**, 1–12.
Jos G.J. Olivier (PBL), Greet Janssens-Maenhout (EC-JRC), Marilena Muntean (EC-JRC), J. A. H. W. P. (PBL), 2013: Trends in global CO2 emissions 2016 report.
Jude, S. R., G. H. Drew, S. J. T. Pollard, S. A. Rocks, K. Jenkinson, and R. Lamb, 2017: Delivering organisational adaptation through legislative mechanisms: Evidence from the Adaptation Reporting Power (Climate Change Act 2008). *Sci. Total Environ.*, **574**, 858–871, doi:10.1016/j.scitotenv.2016.09.104. http://www.sciencedirect.com/science/article/pii/S0048969716320320 (Accessed April 4, 2017).
KC, S., and W. Lutz, 2014: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004. http://www.sciencedirect.com/science/article/pii/S0959378014001095 (Accessed April 8, 2017).
Keith, D. W., and P. J. Irvine, 2016: Solar geoengineering could substantially reduce climate risks - a research hypothesis for the next decade. *Earth's Futur.*, **4**, 2016EF000465, doi:10.1002/2016EF000465.
Keith, D. W., and D. G. MacMartin, 2015: A temporary, moderate and responsive scenario for solar geoengineering. *Nat. Clim. Chang.*, **5**, 201–206. http://dx.doi.org/10.1038/nclimate2493.
Keith, D. W., D. K. Weisenstein, J. A. Dykema, and F. N. Keutsch, 2016: Stratospheric solar geoengineering without ozone loss. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, 14910–14914, doi:10.1073/pnas.1615572113.
Kennedy, C. A., and Coauthors, 2015: Energy and material flows of megacities. *Pnas*, **112**, 5985–5990, doi:10.1073/pnas.1504315112.
Kharas, H., 2014: Financing the post-2015 Sustainable Development Goals: A rough roadmap . *Overseas Dev. Inst.*,.
Kim, R. E., 2016: The Nexus between International Law and the Sustainable Development Goals. *Rev. Eur. Comp. Int. Environ. Law*, **25**, 15–26, doi:10.1111/reel.12148. http://doi.wiley.com/10.1111/reel.12148.
Knopf, B., and Coauthors, 2013: Beyond 2020 — Strategies and Costs for Transforming the European Energy System.

Clim. Chang. Econ., **4**, 1340001, doi:10.1142/S2010007813400010. http://www.worldscientific.com/doi/abs/10.1142/S2010007813400010 (Accessed April 6, 2017).
Kober, T., B. C. C. Van Der Zwaan, and H. Rösler, 2014: Emission Certificate Trade and Costs Under Regional Burden-Sharing Regimes for a 2°C Climate Change Control Target. *Clim. Chang. Econ.*, **5**, 1440001, doi:10.1142/S2010007814400016. http://www.worldscientific.com/doi/abs/10.1142/S2010007814400016 (Accessed April 7, 2017).
Koff, H., 2017: Diaspora Philanthropy in the Context of Policy Coherence for Development: Implications for the post-2015 Sustainable Development Agenda. *Int. Migr.*, **55**, 5–19, doi:10.1111/imig.12277. http://doi.wiley.com/10.1111/imig.12277.
Kravitz, B., D. G. Macmartin, H. Wang, and P. J. Rasch, 2016: Geoengineering as a design problem. *Earth Syst. Dyn.*, **7**, 469–497, doi:10.5194/esd-7-469-2016.
Krey, V., and Coauthors, 2012: Urban and rural energy use and carbon dioxide emissions in Asia. *Energy Econ.*, **34**, S272–S283, doi:10.1016/j.eneco.2012.04.013. http://www.scopus.com/inward/record.url?eid=2-s2.0-84870553992&partnerID=40&md5=000fc5bd314e96ec58bf9aceb09d78ec.
Krey, V., and L. Clarke, 2011: Role of renewable energy in climate mitigation: a synthesis of recent scenarios. *Clim. Policy*, **11**, 1131–1158, doi:10.1080/14693062.2011.579308. http://www.tandfonline.com/loi/tcpo20.
Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Clim. Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.
Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Clim. Change*, **122**, 401–414, doi:10.1007/s10584-013-0971-5. http://dx.doi.org/10.1007/s10584-013-0971-5.
Kriegler, E., and Coauthors, 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change*, **123**, 353–367, doi:10.1007/s10584-013-0953-7.
Kumarappa, J. C., 1949: Science and progress. 1–3.
Kyle, P., E. G. R. Davies, J. J. Dooley, S. J. Smith, L. E. Clarke, J. a. Edmonds, and M. Hejazi, 2013: Influence of climate change mitigation technology on global demands of water for electricity generation. *Int. J. Greenh. Gas Control*, **13**, 112–123, doi:10.1016/j.ijggc.2012.12.006.
Lamb, W. F., and N. D. Rao, 2015: Human development in a climate-constrained world: What the past says about the future. *Glob. Environ. Chang.*, **33**, 14–22, doi:10.1016/j.gloenvcha.2015.03.010. http://dx.doi.org/10.1016/j.gloenvcha.2015.03.010.
Lambin, E. F., 2005: Conditions for sustainability of human–environment systems: Information, motivation, and capacity. *Glob. Environ. Chang.*, **15**, 177–180, doi:10.1016/j.gloenvcha.2005.06.002. http://www.sciencedirect.com/science/article/pii/S0959378005000312 (Accessed April 13, 2017).
Lambini, C. K., 2016: Internalising solar radiation management technological externalities: An ethical review on the design of economic instruments. *Adv. Clim. Chang. Res.*, **7**, 109–112, doi:10.1016/j.accre.2016.04.003.
Lane, L., and W. D. Montgomery, 2014: An institutional critique of new climate scenarios. *Clim. Change*, **122**, 447–458, doi:10.1007/s10584-013-0919-9.
Latham, J., A. Gadian, J. Fournier, B. Parkes, P. Wadhams, and J. Chen, 2014: Marine cloud brightening: regional applications. *Philos. Trans. A. Math. Phys. Eng. Sci.*, **372**, 20140053-, doi:10.1098/rsta.2014.0053.
Lawrence, M. G., 2006: Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative? **2**, doi:10.1002/2016EF000463.
Le Blanc, D., 2015: Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustain. Dev.*, **187**, 176–187, doi:10.1002/sd.1582.
Lesnikowski, A., J. Ford, R. Biesbroek, L. Berrang-Ford, M. Maillet, M. Araos, and S. E. Austin, 2016: What does the Paris Agreement mean for adaptation? *Clim. Policy*, 1–5, doi:10.1080/14693062.2016.1248889. http://dx.doi.org/10.1080/14693062.2016.1248889.
Lewandowski, M., and Mateusz, 2016: Designing the Business Models for Circular Economy—Towards the Conceptual Framework. *Sustainability*, **8**, 43, doi:10.3390/su8010043.
Linder, M., and M. Williander, 2017: Circular Business Model Innovation: Inherent Uncertainties. *Bus. Strateg. Environ.*, **26**, 182–196, doi:10.1002/bse.1906.
Liu, J., and Coauthors, 2015: Systems integration for global sustainability. *Science (80-.).*, **347**, 1258832, doi:10.1126/science.1258832.
Loewe, M., 2012: Post 2015 : How to Reconcile the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs)? *Ger. Dev. Inst.*, 4.
Lucas, P. L., P. R. Shukla, W. Chen, B. J. van Ruijven, S. Dhar, M. G. J. den Elzen, and D. P. van Vuuren, 2013: Implications of the international reduction pledges on long-term energy system changes and costs in China and India. *Energy Policy*, **63**, 1032–1041, doi:10.1016/j.enpol.2013.09.026. http://www.sciencedirect.com/science/article/pii/S0301421513009506 (Accessed April 6, 2017).
Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies

on long-term mitigation pathways. *Clim. Change*, **136**, 127–140, doi:10.1007/s10584-013-0899-9.
Lüken, M., O. Edenhofer, B. Knopf, M. Leimbach, G. Luderer, and N. Bauer, 2011: The role of technological availability for the distributive impacts of climate change mitigation policy. *Energy Policy*, **39**, 6030–6039, doi:http://dx.doi.org/10.1016/j.enpol.2011.07.002. http://www.sciencedirect.com/science/article/pii/S0301421511005258.
Machado, A., 2014: Current science. *Neuromodulation*, **17**, 300–302, doi:10.1111/ner.12182. http://doi.wiley.com/10.1111/ner.12182.
Magnan, A. K., T. Ribera, and S. Treyer, 2015: *National adaptation is also a global concern*. 16 pp. http://www.iddri.org/Publications/National-adaptation-is-also-a-global-concern.
Magnan, A. K., and T. Ribera, 2016: Global adaptation after Paris. *Science (80-.).*, **352**, 1280 LP-1282.
Markandya, A., E. De Cian, L. Drouet, J. M. Polanco-Martìnez, and F. Bosello, 2016: *Building uncertainty into the adaptation cost estimation in integrated assessment models*. Milan, Italy, https://ssrn.com/abstract=2745825.
Marshall, R. J., and J. R. Parratt, 1975: Antiarrhythmic, haemodynamic and metabolic effects of 3alpha-amino-5alpha-androstan-2beta-ol-17-one hydrochloride in greyhounds following acute coronary artery ligation. *Br. J. Pharmacol.*, **55**, 359–368, doi:10.3390/su7021651. http://www.ncbi.nlm.nih.gov/pubmed/1133.
Mathiesen, B. V., and Coauthors, 2015: Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Appl. Energy*, **145**, 139–154, doi:10.1016/j.apenergy.2015.01.075.
McClellan, J., D. W. Keith, and J. Apt, 2012: Cost analysis of stratospheric albedo modification delivery systems. *Environ. Res. Lett.*, **7**, 34019, doi:10.1088/1748-9326/7/3/034019.
McCollum, D. L., V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, and N. Nakicenovic, 2013: Climate policies can help resolve energy security and air pollution challenges. *Clim. Change*, **119**, 479–494, doi:10.1007/s10584-013-0710-y. http://dx.doi.org/10.1007/s10584-013-0710-y.
McCollum, D., V. Krey, P. Kolp, Y. Nagai, and K. Riahi, 2014: Transport electrification: A key element for energy system transformation and climate stabilization. *Clim. Change*, **123**, 651–664, doi:10.1007/s10584-013-0969-z.
McGray, H., A. Hammill, R. Bradley, and E. Schipper, 2007: *Weathering the storm: Options for framing adaptation and development*. http://www.wri.org/sites/default/files/pdf/infosheet_weathering_the_storm.pdf (Accessed April 8, 2017).
McLaren, D., 2016: Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Futur.*, **4**, 596–602, doi:10.1002/2016EF000445.
Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley, 2011: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmos. Chem. Phys.*, **11**, 1417–1456, doi:10.5194/acp-11-1417-2011.
Mileva, A., J. Johnston, J. H. Nelson, and D. M. Kammen, 2016: Power system balancing for deep decarbonization of the electricity sector. *Appl. Energy*, **162**, 1001–1009, doi:10.1016/j.apenergy.2015.10.180.
Miller, C. A., J. Richter, and J. O'Leary, 2015: Socio-energy systems design: A policy framework for energy transitions. *Energy Res. Soc. Sci.*, **6**, 29–40, doi:10.1016/j.erss.2014.11.004.
Minx, J., W. F. Lamb, M. W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environ. Res. Lett.*, **12**. http://iopscience.iop.org/1748-9326/12/3/035007.
Moriyama, R., M. Sugiyama, A. Kurosawa, K. Masuda, K. Tsuzuki, and Y. Ishimoto, 2016: The cost of stratospheric climate engineering revisited. *Mitig. Adapt. Strateg. Glob. Chang.*, 1–22, doi:10.1007/s11027-016-9723-y.
Morseletto, P., F. Biermann, and P. Pattberg, 2016: Governing by targets: reductio ad unum and evolution of the two-degree climate target. *Int. Environ. Agreements Polit. Law Econ.*, 1–22, doi:10.1007/s10784-016-9336-7. http://link.springer.com/10.1007/s10784-016-9336-7.
Muri, H., J. E. Kristjánsson, T. Storelvmo, and M. A. Pfeffer, 2014: The climatic effects of modifying cirrus clouds in a climate engineering framework. *J. Geophys. Res. Atmos.*, **119**, 4174–4191, doi:10.1002/2013JD021063.
Nair, S., B. George, H. M. Malano, M. Arora, and B. Nawarathna, 2014: Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resour. Conserv. Recycl.*, **89**, 1–10, doi:10.1016/j.resconrec.2014.05.007.
Neill, B. C., K. Riahi, and I. Keppo, 2010: Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proc. Natl. Acad. Sci. U. S. A.*, **107**, 1011–1016, doi:10.1073/pnas.0903797106.
Newman, P., 2017: Decoupling Economic Growth from Fossil Fuels. *Mod. Econ.*,.
Nowack, P. J., N. L. Abraham, P. Braesicke, and J. A. Pyle, 2016: Stratospheric ozone changes under solar geoengineering: Implications for UV exposure and air quality. *Atmos. Chem. Phys.*, **16**, 4191–4203, doi:10.5194/acp-16-4191-2016.
Nugent, D., and B. K. Sovacool, 2014: Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*, **65**, 229–244, doi:10.1016/j.enpol.2013.10.048.
Ockwell, D., A. Sagar, and H. de Coninck, 2014: Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach. *Clim. Change*, **131**, 401–415, doi:10.1007/s10584-014-1123-2.
Olivier, J. G. J., G. Janssens-Maenhout, and J. A. H. W. Peters, 2012: *Trends in Global CO_2 Emissions; 2012 Report*.

PBL Netherlands Environmental Assessment Agency, Institute for Environment and Sustainability (IES) of the European Commission's Joint Research Centre (JRC), The Hague, Netherlands, 42 pp. http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2012_Trends_in_global_CO2_emissions_500114022.pdf.

Olsson, P., M. Opondo, P. Tschakert, A. Agrawal, S. H. Eriksen, S. Ma, L. N. Perch, and S. A. Zakieldeen, 2014: Livelihoods and poverty. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change2*, 793–832.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change*, **122**, 387–400, doi:10.1007/s10584-013-0905-2. http://dx.doi.org/10.1007/s10584-013-0905-2.

O'Neill, B. C., and Coauthors, 2017: IPCC reasons for concern regarding climate change risks. *Nat. Clim. Chang.*, **7**, 28–37. http://dx.doi.org/10.1038/nclimate3179.

O'Neill, D. W., 2015: The proximity of nations to a socially sustainable steady-state economy. *J. Clean. Prod.*, **108**, 1213–1231, doi:10.1016/j.jclepro.2015.07.116. http://www.sciencedirect.com/science/article/pii/S0959652615010471 (Accessed April 8, 2017).

Ostrom, E., J. Burger, C. B. Field, R. B. Norgaard, and D. Policansky, 1999: Revisiting the Commons: Local Lessons, Global Challenges. *Science (80-.).*, **284**. http://science.sciencemag.org/content/284/5412/278 (Accessed April 9, 2017).

Pachauri, R. K., and Coauthors, 2014: *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC,.

Peters, G. P., R. M. Andrew, J. G. Canadell, S. Fuss, R. B. Jackson, J. I. Korsbakken, C. Le Quéré, and N. Nakicenovic, 2017: Key indicators to track current progress and future ambition of the Paris Agreement. *Nat. Clim. Chang.*, **7**, 118–122, doi:10.1038/nclimate3202.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The "2°C capital stock" for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Appl. Energy*, **179**, 1395–1408, doi:http://dx.doi.org/10.1016/j.apenergy.2016.02.093. http://www.sciencedirect.com/science/article/pii/S0306261916302495.

Pitari, G., and Coauthors, 2014: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **119**, 2629–2653, doi:10.1002/2013JD020566.

Quaas, J., M. F. Quaas, O. Boucher, and W. Rickels, 2016: Regional climate engineering by radiation management: Prerequisites and prospects. *Earth's Futur.*, **4**, 618–625, doi:10.1002/2016EF000440. http://doi.wiley.com/10.1002/2016EF000440 (Accessed April 13, 2017).

Rao, N. D., 2013: Distributional impacts of climate change mitigation in Indian electricity: The influence of governance. *Energy Policy*, **61**, 1344–1356, doi:10.1016/j.enpol.2013.05.103.

Rao, S., S. Pachauri, F. Dentener, P. Kinney, Z. Klimont, K. Riahi, and W. Schoepp, 2013: Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. *Glob. Environ. Chang.*, **23**, 1122–1130, doi:10.1016/j.gloenvcha.2013.05.003.

Reid, H., M. Alam, R. Berger, T. Cannon, M. Huq, S., and A. Milligan, 2009: Community-based adaptation to climate change: An overview. *Participatory learning 60: Community-based adaptation to climate change*, H. Ashley and A. Milligan, Eds., International Institute for Environment and Development.

Resnick, D., F. Tarp, and J. Thurlow, 2012: The Political Economy of Green Growth: Cases from Southern Africa. *Public Adm. Dev.*, **32**, 215–228, doi:10.1002/pad.1619. http://doi.wiley.com/10.1002/pad.1619 (Accessed April 12, 2017).

Revi, A., and Coauthors, 2014: Towards transformative adaptation in cities: the IPCC's Fifth Assessment. *Environ. Urban.*, **26**, 11–28.

Reynolds, J. L., A. Parker, and P. Irvine, 2016: Five solar geoengineering tropes that have outstayed their welcome. *Earth's Futur.*, doi:10.1002/2016EF000416.Abstract.

Riahi, K., and Coauthors, 2015: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*.

Ribot, J. C., 2001: *Local Actors , Powers and Accountability in African Decentralizations : A Review of Issues*.

Riccardo Pavoni, Piselli, D., 2016: the Sustainable Development Goals and International Environmental Law : Normative Value and Challenges for Implementation. *Veredas do Direito, Belo Horizonte*, **13**, 13–60. http://www.domhelder.edu.br/revista/index.php/veredas/article/viewFile/865/496.

Rice, J. L., B. J. Burke, and N. Heynen, 2015: Knowing climate change, embodying climate praxis: Experiential knowledge in Southern Appalachia. *Ann. Assoc. Am. Geogr.*, **105**, 253–262, doi:10.1080/00045608.2014.985628.

Rivera-Ferre, M. G., F. López-i-Gelats, M. Howden, P. Smith, J. F. Morton, and M. Herrero, 2016: Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. *Wiley Interdiscip. Rev. Clim. Chang.*, **7**, 869–892, doi:10.1002/wcc.421.

Robock, A., 2016: Albedo enhancement by stratospheric sulfur injections: More research needed. *Earth's Futur.*, **4**, 644–648, doi:10.1002/2016EF000407.

Roelfsema, M., M. Harmsen, J. Olivier, and A. Hof, 2015: *Climate Action outside the UNFCCC*. The Hague, Netherlands, 1-40 pp. http://www.pbl.nl/sites/default/files/cms/pbl-2015-climate-action-outside-the-unfccc_01188.pdf.

Rogelj, J. and M. M. and M. S. and R. K. and K., 2015: Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. *Environ. Res. Lett.*, **10**, 75001, doi:10.1088/1748-9326/10/7/075001.

Rogelj, J., and Coauthors, 2016: Perspective : Paris Agreement climate proposals need boost to keep warming well below 2 ° C. *Nat. Clim. Chang.*, **534**, 631–639, doi:10.1038/nature18307.

Rogelj, J., and Coauthors, 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Chang.*, **1**, 413–418, doi:10.1038/nclimate1258. http://dx.doi.org/10.1038/nclimate1258.

Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi, 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.*, **5**, 519–527, doi:10.1038/nclimate2572.

Rohracher, H., and P. Späth, 2014: The Interplay of Urban Energy Policy and Socio-technical Transitions: The Eco-cities of Graz and Freiburg in Retrospect. *Urban Stud.*, **51**, 1415–1431, doi:10.1177/0042098013500360.

Roques, F. A., D. M. Newbery, and W. J. Nuttall, 2008: Fuel mix diversification incentives in liberalized electricity markets: A Mean--Variance Portfolio theory approach. *Energy Econ.*, **30**, 1831–1849.

Rothman, D. S., P. Romero-Lankao, V. J. Schweizer, and B. A. Bee, 2014: Challenges to adaptation: a fundamental concept for the shared socio-economic pathways and beyond. *Clim. Change*, **122**, 495–507, doi:10.1007/s10584-013-0907-0.

Rozenberg, J., C. Guivarch, R. Lempert, and S. Hallegatte, 2014: Building SSPs for climate policy analysis: A scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. *Clim. Change*, **122**, 509–522, doi:10.1007/s10584-013-0904-3.

Rutherford, J., and O. Coutard, 2014: Urban Energy Transitions: Places, Processes and Politics of Socio-technical Change. *Urban Stud.*, **51**, 1353–1377, doi:10.1177/0042098013500090.

Ryaboshapko A.G., R. A. P., 2015: Technical capabilities for creating an aerosol layer in the stratosphere for climate stabilization purpose (in Russian). *Probl. Environ. Monit. Ecosyst. Model.*, **26**, 115–127.

Samet, R. H., 2013: Complexity, the science of cities and long-range futures. *Futures*, **47**, 49–58, doi:10.1016/j.futures.2013.01.006. http://www.sciencedirect.com/science/article/pii/S0016328713000074 (Accessed April 6, 2017).

Sano, F., K. Wada, K. Akimoto, and J. Oda, 2015: Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro- and sectoral decomposition analyses. *Technol. Forecast. Soc. Change*, **90**, 153–165, doi:10.1016/j.techfore.2013.11.002. http://www.sciencedirect.com/science/article/pii/S0040162513002862 (Accessed April 6, 2017).

Savo, V., D. Lepofsky, J. P. Benner, K. E. Kohfeld, J. Bailey, and K. Lertzman, 2016: Observations of climate change among subsistence-oriented communities around the world. *Nat. Clim. Chang.*, **6**, 462–473.

Schipper, E. L. F., 2007: Climate Change Adaptation and Development : Exploring the Linkages. *Change*, **107**, 20.

Schipper, E., J. Ayers, H. Reid, S. Huq, and A. Rahman, 2014: *Community-based adaptation to climate change: scaling it up*. https://books.google.com.gt/books?hl=en&lr=&id=zw-pAgAAQBAJ&oi=fnd&pg=PP1&dq=Schipper+ELF,+Ayers+J,+Reid+H,+Huq+S,+Rahman+A+(2014)+Community+based+adaptation+to+climate+change:+scaling+it+up.+Routledge,+London.&ots=6hFO8SAGxB&sig=-Sk0k_7SZWRcOSKo5w_wdHfSF (Accessed April 8, 2017).

Schleussner, C.-F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C. *Earth Syst. Dyn.*, **7**, 327–351, doi:10.5194/esd-7-327-2016.

Schmidt-Traub, G., 2015: Investment Needs to Achieve the Sustainable Development Goals Understanding the Billions and Trillions. *SDSN Work. Pap.*, **Version 2**, 1–137. http://unsdsn.org/resources/publications/sdg-investment-needs/.

Schwanitz, V. J., T. Longden, B. Knopf, and P. Capros, 2015: The implications of initiating immediate climate change mitigation - A potential for co-benefits? *Technol. Forecast. Soc. Change*, **90**, 166–177, doi:10.1016/j.techfore.2014.01.003.

Schwanitz, V. J., F. Piontek, C. Bertram, and G. Luderer, 2014: Long-term climate policy implications of phasing out fossil fuel subsidies. *Energy Policy*, **67**, 882–894, doi:10.1016/j.enpol.2013.12.015. http://www.sciencedirect.com/science/article/pii/S0301421513012597 (Accessed April 6, 2017).

Schweizer, V. J., B. C. O. ' Neill, V. J. Schweizer, and B. C. O. ' Neill, 2014: Systematic construction of global socioeconomic pathways using internally consistent element combinations. *Clim. Change*, **122**, 431–445, doi:10.1007/s10584-013-0908-z.

SED, 2015: Report on the structured Expert dialogue on the 2013-2015 review.

Sgouridis, S., D. Csala, and U. Bardi, 2016: The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environ. Res. Lett.*, **11**, 94009, doi:10.1088/1748-9326/11/9/094009.

Shafiei, E., B. Davidsdottir, J. Leaver, H. Stefansson, and E. I. Asgeirsson, 2017: Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity. *J. Clean. Prod.*, **141**, 237–247, doi:10.1016/j.jclepro.2016.09.064.

Sherman, M., and Coauthors, 2016: Drawing the line between adaptation and development: a systematic literature review of planned adaptation in developing countries. *Wiley Interdiscip. Rev. Clim. Chang.*, **7**, 707–726, doi:10.1002/wcc.416.

Shukla, P., and et al., 2017: *How to use SVMAs to reduce the Carbon Pricing and Climate Finance Ga: Numerical Illustrations*.

Singh, C., P. Dorward, and H. Osbahr, 2016: Developing a holistic approach to the analysis of farmer decision-making: Implications for adaptation policy and practice in developing countries. *Land use policy*, **59**, doi:10.1016/j.landusepol.2016.06.041.

Sirkis, A., and Coauthors, 2015: Moving the Trillions. A Debate on Positive Pricing of Mitigation Actions. *Cent. Bras. no Clima Ed./CIRED, Nogent-sur-Marne*,.

Smith, C. J., and Coauthors, 2017: Impacts of stratospheric sulfate geoengineering on global solar photovoltaic and concentrating solar power resource. *J. Appl. Meteorol. Climatol.*, JAMC-D-16-0298.1, doi:10.1175/JAMC-D-16-0298.1. http://journals.ametsoc.org/doi/10.1175/JAMC-D-16-0298.1 (Accessed April 8, 2017).

Smith, P., and Coauthors, 2016: Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.*, **6**, doi:10.1038/nclimate2870.

Smith, P., Z. Martino, and D. et al. Cai, 2007: *Working Group II, Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Glob. Chang. Biol.*, **22**, 1315–1324, doi:10.1111/gcb.13178.

Smith, P., M. Bustamante, P. S. Uk, and M. B. Brazil, 2014: *AR5 WGIII Chapter 11 - Agriculture, Forestry and Other Land Use (AFOLU)*. 811-922 pp.

Smith, P., and Coauthors, 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Chang. Biol.*, **19**, 2285–2302, doi:10.1111/gcb.12160.

Sovacool, B. K., 2014: Energy studies need social science. *Nature*, **511**, 529–530, doi:10.1016/j.jeem.2008.02.004.

Stainforth, D. ., M. . Allen, E. . Tredger, and L. . Smith, 2007: Confidence, uncertainty and decision-support relevance in climate predictions. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **365**, 2145–2161, doi:10.1098/rsta.2007.2074. http://rsta.royalsocietypublishing.org/content/365/1857/2145.abstract (Accessed July 21, 2011).

Steckel, L. H. and J. C., 2016: The role of capital costs in decarbonizing the electricity sector. *Environ. Res. Lett.*, **11**, 114010.

Steg, L., 2016: Values, Norms, and Intrinsic Motivation to Act Proenvironmentally. *Annu. Rev. Environ. Resour.*, **41**, 277–292, doi:10.1146/annurev-environ-110615-085947.

Svoboda, T., 2016: Aerosol Geoengineering Deployment and Fairness. *Environ. Values*, **25**, 51–68, doi:10.3197/096327115X14497392134883. http://openurl.ingenta.com/content/xref?genre=article&issn=0963-2719&volume=25&issue=1&spage=51 (Accessed April 8, 2017).

Termeer, C. J. A. M., A. Dewulf, and G. R. Biesbroek, 2017: Journal of Environmental Planning and Management Transformational change: governance interventions for climate change adaptation from a continuous change perspective Transformational change: governance interventions for climate change adaptation from a co. *J. Environ. Plan. Manag.*, **604**, 558–576, doi:10.1080/09640568.2016.1168288. http://www.tandfonline.com/action/journalInformation?journalCode=cjep20 (Accessed April 8, 2017).

Termeer, C. J. A. M., A. Dewulf, and G. R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *J. Environ. Plan. Manag.*, **60**, 558–576.

Terrapon-Pfaff, J., C. Dienst, J. König, and W. Ortiz, 2014: A cross-sectional review: Impacts and sustainability of small-scale renewable energy projects in developing countries. *Renew. Sustain. Energy Rev.*, **40**, 1–10, doi:10.1016/j.rser.2014.07.161.

Thomson, G., and P. Newman, 2016: Geoengineering in the Anthropocene through Regenerative Urbanism. *Geosciences*, **6**.

Tidwell, V. C., J. Macknick, K. Zemlick, J. Sanchez, and T. Woldeyesus, 2014: Transitioning to zero freshwater withdrawal in the U.S. for thermoelectric generation. *Appl. Energy*, **131**, 508–516, doi:10.1016/j.apenergy.2013.11.028.

Tilmes, S., B. M. Sanderson, and B. C. O'Neill, 2016: Climate impacts of geoengineering in a delayed mitigation scenario. *Geophys. Res. Lett.*, **43**, 8222–8229, doi:10.1002/2016GL070122.

Tschakert, P., B. van Oort, A. L. St. Clair, and A. LaMadrid, 2013: Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. *Clim. Dev.*, **5**, 340–350, doi:10.1080/17565529.2013.828583. http://www.tandfonline.com/doi/abs/10.1080/17565529.2013.828583 (Accessed April 8, 2017).

UNEP, 2016: *The Adaptation Finance Gap Report 2016*. Nairobi, Kenya, http://web.unep.org/adaptationgapreport/2016.

UNFCCC, 2015: Adoption of the Paris Agreement. Proposal by the President. *Paris Clim. Chang. Conf. - Novemb. 2015, COP 21*, **21932**, 32, doi:FCCC/CP/2015/L.9/Rev.1. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

UNFCCC, 1992: United Nations Framework Convention on Climate Change. *United Nations*, doi:10.1111/j.1467-9388.1992.tb00046.x. http://doi.wiley.com/10.1111/j.1467-9388.1992.tb00046.x.

United Nations, 2015: World Population Prospects - 2015 Revision. *World Popul. Prospect. Div. Nations*,.

Van den Bergh, J. C. J. ., 2011: Environment versus growth—A criticism of "degrowth" and a plea for "a-growth." *Ecol. Econ.*, **70**, 881–890.

van der Werff, E., L. Steg, and K. Keizer, 2014: Follow the signal: When past pro-environmental actions signal who you are. *J. Environ. Psychol.*, **40**, 273–282, doi:http://dx.doi.org/10.1016/j.jenvp.2014.07.004.

Van der Werff, E., L. Steg, and K. Keizer, 2013: It is a moral issue: The relationship between environmental self-identity, obligation-based intrinsic motivation and pro-environmental behaviour. *Glob. Environ. Chang.*, **23**, 1258–1265, doi:10.1016/j.gloenvcha.2013.07.018.

van Ruijven, B. J., and Coauthors, 2014: Enhancing the relevance of shared socioeconomic pathways for climate change impacts, adaptation and vulnerability research. *Clim. Change*, **122**, 481–494, doi:10.1007/s10584-013-0931-0.

van Sluisveld, M. A. E., and Coauthors, 2015: Comparing future patterns of energy system change in 2??C scenarios with historically observed rates of change. *Glob. Environ. Chang.*, **35**, 436–449, doi:10.1016/j.gloenvcha.2015.09.019. http://dx.doi.org/10.1016/j.gloenvcha.2015.09.019.

van Vuuren, D. P., and T. R. Carter, 2014: Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Clim. Change*, **122**, 415–429, doi:10.1007/s10584-013-0974-2.

van Vuuren, D. P., J. Cofala, H. E. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M. G. J. den Elzen, and M. Amann, 2006: Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy*, **34**, 444–460, doi:10.1016/j.enpol.2004.06.012.

van Vuuren, D. P., and Coauthors, 2014: A new scenario framework for Climate Change Research: Scenario matrix architecture. *Clim. Change*, **122**, 373–386, doi:10.1007/s10584-013-0906-1.

van Vuuren, D. P., and Coauthors, 2015: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*.

Venter, Z., H.-J. Hawkins, and M. Cramer, Implications of historical interactions between herbivory and fire for rangeland management in African savannas adaptively manipulating herbivore densities over time and space and diversifying herbivore functional guilds.

Villarroel Walker, R., M. B. Beck, J. W. Hall, R. J. Dawson, and O. Heidrich, 2014: The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *J. Environ. Manage.*, **141**, 104–115, doi:10.1016/j.jenvman.2014.01.054.

Visioni, D., G. Pitari, and V. Aquila, 2016: Sulfate geoengineering: a review of the factors controlling the needed injection of sulfur dioxide. *Atmos. Chem. Phys. Discuss*, 3879–3889, doi:doi:10.5194/acp-2016-985, 2016.

Vlek, C., and L. Steg, 2007: Human behavior and environmental sustainability: Problems, driving forces, and research topics. *J. Soc. Issues*, **63**, 1–19, doi:10.1111/j.1540-4560.2007.00493.x. http://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=9&SID=V1ih1no9GeCmN3OpPad&page=1&doc=4 (Accessed April 4, 2017).

von Stechow, C., and Coauthors, 2016: 2 °C and SDGs: united they stand, divided they fall? *Environ. Res. Lett.*, **11**, 34022, doi:10.1088/1748-9326/11/3/034022. http://stacks.iop.org/1748-9326/11/i=3/a=034022?key=crossref.d54cd14d11ea3456641caebf1c660240.

Wang, H., P. J. Rasch, and G. Feingold, 2011: Manipulating marine stratocumulus cloud amount and albedo: A process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei. *Atmos. Chem. Phys.*, **11**, 4237–4249, doi:10.5194/acp-11-4237-2011.

Wang, Q., F. Xiao, F. Zhang, and S. Wang, 2013: Labile soil organic carbon and microbial activity in three subtropical plantations. *Forestry*, **86**, 569–574, doi:10.1093/forestry/cpt024.

Weaver, C. P., and Coauthors, 2014: From global change science to action with social sciences. *Nat. Clim. Chang.*, **4**, 656–659. http://dx.doi.org/10.1038/nclimate2319.

Weigt, H., D. Ellerman, and E. Delarue, 2013: CO2 abatement from renewables in the German electricity sector: Does a CO2 price help? *Energy Econ.*, **40**, S149–S158, doi:10.1016/j.eneco.2013.09.013.

Weigt, H., D. Ellerman, and E. Delarue, 2013: CO2 abatement from renewables in the German electricity sector: Does a CO2 price help? *Energy Econ.*, **40**, S149–S158, doi:10.1016/j.eneco.2013.09.013.

Weitzman, M. L., 2015: A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *Scand. J. Econ.*, **117**, 1049–1068, doi:10.1111/sjoe.12120.

Wilbanks, T. J., and K. L. Ebi, 2013: SSPs from an impact and adaptation perspective. *Clim. Change*, **122**, 473–479, doi:10.1007/s10584-013-0903-4.

Williamson, P., 2016: Emissions reduction: Scrutinize CO2 removal methods. *Nature*, **530**, 5–7, doi:10.1038/530153a. http://www.nature.com/news/emissions-reduction-scrutinize-co2-removal-methods-1.19318.
Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? *Clim. Change*, **118**, 381–395, doi:10.1007/s10584-012-0618-y.
Wimmer, F., E. Audsley, M. Malsy, C. Savin, R. Dunford, P. A. Harrison, R. Schaldach, and M. Flörke, 2014: Modelling the effects of cross-sectoral water allocation schemes in Europe. *Clim. Change*, **128**, 229–244, doi:10.1007/s10584-014-1161-9.
Wise, R. M., and Coauthors, 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ.*, **28**, 325–336, doi:10.1016/j.gloenvcha.2013.12.002.
Wolbring, G., R. Mackay, T. Rybchinski, and J. Noga, 2013: Disabled People and the Post-2015 Development Goal Agenda through a Disability Studies Lens. *Sustainability*, **5**, 4152–4182, doi:10.3390/su5104152. http://www.mdpi.com/2071-1050/5/10/4152/.
Wollenberg, E., and Coauthors, 2016: Reducing emissions from agriculture to meet the 2C target. *Glob. Chang. Biol.*, **22**, 3859–3864, doi:10.1111/gcb.13340.
Wong, P.-H., 2014: Maintenance Required: The Ethics of Geoengineering and Post-Implementation Scenarios. *Ethics, Policy Environ.*, **17**, 186–191, doi:10.1080/21550085.2014.926090.
World Bank, 2015: *World Development Report 2015. Vol. 53*.
Yang, L., H. Yan, and J. C. Lam, 2014: Thermal comfort and building energy consumption implications - A review. *Appl. Energy*, **115**, 164–173, doi:10.1016/j.apenergy.2013.10.062.
Young, O. R., 2016: *Governing Complex Systems: Social Capital for the Anthropocene*. MIT Press,.
Zenghelis, D., 2012: *A strategy for restoring confidence and economic growth through green investment and innovation*. London, UK,.
Ziervogel, G., A. Cartwright, A. Tas, J. Adejuwon, F. Zermoglio, M. Shale, and B. Smith, 2008: *Climate change and adaptation in African agriculture*.
Ziervogel, G., A. Cowen, and J. Ziniades, 2016: Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements. *Sustainability*, **8**, 955.
Ziervogel, G., and Coauthors, 2017: Inserting Rights and Justice into Urban Resilience: A Focus on Everyday Risk. *Environ. Urban.*, 95624781668690, doi:10.1177/0956247816686905.

Chapter 5: Sustainable Development, Poverty Eradication and Reducing Inequalities

Coordinating Lead Authors: Roy Joyashree (India), Tschakert Petra (Australia)

Lead Authors: Abdul Halim Sharina (Malaysia), Dasgupta Purnamita (India), Hayward Bronwyn (New Zealand), Kanninen Markku (Finland), Kovats Sari (United Kingdom of Great Britain and Northern Ireland), Liverman Diana (United States of America), Ochieng Cosmas (Kenya), Pinho Patricia Fernanda (Brazil), Riahi Keywan (Austria), Suarez Rodriguez Avelino G. (Cuba), Urquhart Penny (South Africa), Waisman Henri (France)

Contributing Authors:

Review Editors: Krakovska Svitlana (Ukraine), Pichs Madruga Ramon (Cuba), Sanchez Roberto (Mexico)

Chapter Scientist: Ellis Neville (Australia)

Date of Internal Draft: 8 April 2017

Executive Summary

5.1 Scope and Delineations

This chapter focuses on the connections between sustainable development and pathways to 1.5 °C and related impacts, especially in relation to the Sustainable Development Goals (SDGs) and reductions in poverty and inequality. It attempts to answer a number of fundamental questions as the final chapter of this Special Report. If sustainable development is an overarching priority cutting across time and space, how might achieving development goals decrease or increase the risks of climate change? How do climatic changes and adaptation and mitigation options and measures to respond to these changes influence the possibilities of meeting the SDGs? What are the synergies and trade-offs between sustainable development and climate action?

This chapter builds on prior IPCC reports and new literature that examines how choices over mitigation and adaptation options affect sustainable development, including efforts to eradicate poverty, reduce inequalities and strive for equity, and what climate-resilient development pathways are possible in the context of a 1.5 °C warmer world. More specifically, the chapter examines both the impacts on sustainable development, both from 1.5 °C global warming and adaptive and mitigative action taken to limit warming to 1.5 °C, with particular emphasis on the SDGs. The chapter also examines the reverse, namely how efforts to pursue sustainable development are expected to affect the chances of reaching the 1.5 °C target as well as human abilities to adapt. Finally, the chapter explores the differences between 1.5 °C and 2 °C emission pathways as they relate to sustainable development and concludes with foundations for and successful examples of climate-resilient development pathways across different scales.

5.1.1 Sustainable Development, Poverty, Equality, and Equity: Core Concepts and Trends

Sustainable development has been defined in many ways. The original concept is often rooted in the 1987 report Our Common Future which stated "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The UN General Assembly accepted sustainable development as balancing economic development, social development and environmental protection. However, the definitions and goals of sustainable development are inconsistent and contested (Escobar 1994; Beckerman 1995; Lele 1991) and measuring it in practice remains a challenge.

The AR5 (Intergovernmental Panel on Climate Change 2015) concluded that climate change constrains possible development paths, that synergies and trade-offs exist between climate responses and sustainable development goals, that capacities for effective climate responses overlap with capacities for sustainable development, and that existing societal patterns (e.g. overconsumption) are intrinsically unsustainable (Fleurbaey et al. 2014). Ch20 WGII noted that climate change constituted “a moderate threat to current sustainable development and a severe threat to future sustainable development” (*high confidence*) and that “ill-designed responses” could “offset already achieved gains” (Denton et al. 2014).

The AR5 acknowledged *multidimensional poverty* and deprivation, not just income-based poverty that is typically measured by using the International Poverty Line of $1.25/day. It stressed the need to take into account other core aspects such as hunger, illiteracy, lack of access or rights to services, living standards, social exclusion and disempowerment (Olsson et al. 2014). Since then, the Multidimensional Poverty Index for 2005-2015 reported nearly 1.5 billion people in developing countries as multidimensionally poor, although deprivation also occurs in high-income countries (UNDP 2016).

The AR5 also provided insight into the geographic distribution and trends of *poverty patterns*, and addressed poverty dynamics, e.g. shifts between transient and chronic poverty, as well as relational aspects of poverty (Olsson et al. 2014). To date, most multidimensionally poor live in South Asia (53.9%) and Sub-Saharan Africa (33.5%), and more in rural than in urban areas (UNDP 2016). Nearly half a billion people are trapped in chronic poverty, meaning poverty over many years, possibly a life time, and the lives of their children (Shepherd et al. 2014). By 2030, projections indicate up to 950 million people still living at $1.25/day, split evenly between low-income countries (LICs) and low-middle-income countries (LMICs), mostly in South Asia, East Africa, and the Sahel; this includes up to 25 countries (pessimistic scenario) with > 10 million poor at this threshold, with the highest number per country in India (between 76-256 million) (Shepherd et al. 2014). More than 20 countries in Africa, as well as Nepal, Honduras, and Haiti, are projected to be highly vulnerable to poverty by 2030 (high numbers and high proportion of poor people) (Shepherd et al. 2014).

Equality and *equity* are intimately tied to sustainable development goals yet are also fraught with definitional problems. Equality ensures all people the same status, opportunities, and rights, yet people embark from different starting points and thus don’t benefit the same way. In the context of global warming, the importance of equality across generations has been articulated in terms of “growth sustainability” (Llavador et al. 2015). Equity is often seen synonymous with fairness and justice, entailing distributive and procedural equity as well as equity between and within generations.

The IPCC Special Report on Extremes Events (SREX) recognized the need address structural inequalities that perpetuate poverty and inequality and create vulnerability as a precondition for dealing with climate change (IPCC et al. 2012). These structural inequalities are overlaid onto income inequalities between and within countries. In 2015, the total wealth of the poorest 50% equaled the wealth of the 62 richest people in the world (Oxfam 2015, cited in (UNESCO and ISSC 2016)). Income inequality has risen along with a rise in incomes (Roine and Waldenström 2015), particularly in high-income countries (e.g. USA and UK) and continues to be even higher in MICs such as South Africa, Brazil, Mexico, India, and China (UNESCO and ISSC 2016). The AR5 explored intersectional dimensions of inequality at smaller scales, along the axes of gender, class, ethnicity, age, race, and (dis)ability, and their relation to vulnerability and risk (Olsson et al. 2014), with the conclusion that multidimensional inequalities, often produced by uneven development processes, shape differential vulnerabilities to and risks from climate change (IPCC 2014a).

The AR5 concluded that ‘climate change and climate variability worsen existing poverty and exacerbate inequalities’ (*high confidence*) and that climate change will ‘create new poor between now and 2100, in developing and developed countries, and jeopardize sustainable development’ (*high confidence*) (Olsson et al. 2014). Furthermore, it concluded that risks from climate change are ‘unevenly distributed and generally greater for disadvantaged people and communities in countries at all level of development’ (IPCC 2014b).

5.1.2 Sustainable Development Goals

The UN Millennium Declaration in 2000 set out an explicit set of development goals which prioritized global reductions in poverty and hunger, improvements in health, education, and gender equity, debt reduction, and improved access to water and sanitation between 1990 and 2015. Considerable success has been claimed in reaching many of the targets of the *Millennium Development Goals* (MDGs), including halving poverty and increasing water security. Critics argued that the MDGs failed to address within country disparities and human rights, were developed by a small group of experts, only focused on developing countries, and had numerous measurement and attribution problems (Amin 2006; Clemens et al. 2007) (Langford 2013).

Building on the successes and limitations of the Millennium Development Goals, the more recent UN *Sustainable Development Goals* have a stronger focus on equity and environment and apply to all countries as global goals (see Box 5.1). They seek to achieve the 'Future We Want' (UN Resolution A/RES/70/1) "action-oriented, concise and easy to communicate, limited in number, aspirational, global in nature and universally applicable to all countries while taking into account different national realities, capacities and levels of development and respecting national policies and priorities".

[START BOX 5.1 HERE]

Box 5.1: The Sustainable Development Goals (SDGs)

In September 2015, the international community endorsed a universal agenda entitled 'Transforming our World: the 2030 Agenda for Sustainable Development', widely known as the Sustainable Development Goals (SDGs). The 17 goals and 169 targets to be met by 2030 were developed with widespread participation and were adopted in 2012 under the rubric of goals for people, prosperity, peace, partnerships and the planet. The preamble to the SDGs announces 'to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path'. With their explicit aim to 'leave no one behind', the SDGs provide a promising basis for addressing inclusive growth, shared prosperity, and multidimensional inequalities (UNRISD 2016). They are seen as an 'indivisible' package of goals that need to be pursued in an integrated way (Coopman et al. 2016); yet, the policy challenges to realize this integration are enormous.

The SDGs include specific goals for climate action (Goal 13), access to affordable and clean energy (Goal 7), sustainable consumption and cities (Goals 11 and 12), and equality/equity goals for gender education, income, work, and access to justice (Goal 5 and transcending several other goals). They go further than the MDGs in seeking to completely end poverty and hunger. Proposed indicators include losses from natural disasters, energy intensity, GHG emissions, and climate finance (http://indicators.report/goals/goal-13/).

Set of 17 aspirational goals with 169 targets, developed in deliberative/participatory process:

Goal 1 No Poverty: End poverty in all its forms everywhere (less than $1.25/day and multidimensional as defined locally)
Goal 2 Zero Hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3 Good Health and Wellbeing: Ensure healthy lives and promote well-being for all at all ages
Goal 4 Quality Educati0n: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5 Gender Equality: Achieve gender equality and empower all women and girls
Goal 6 Clean Water and Sanitation: Ensure availability and sustainable management of water and sanitation for all
Goal 7 Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8 Decent work and Economic Growth: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
Goal 9 Industry, Innovation and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Goal 10 Reduced inequalities: Reduce inequality within and among countries
Goal 11 Sustainable Cities and Communities: Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12 Responsible Consumption and Production: Ensure sustainable consumption and production patterns
Goal 13 Climate action: Take urgent action to combat climate change and its impacts
Goal 14 Life below water: Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15 Life on Land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 16 Peace, Justice and Strong Institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17 Partnerships for the Goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development

Despite their integrative vision, the 2030 Agenda is plagued by friction between some of the goals. Some analysts suggest the SDGs are too complex, lack realistic targets, are focused on 2030 at the expense of longer term objectives, and may contradict each other (Death and Gabay 2015) (Horton 2014). Moreover, there are tensions between the progressive and normative aims on the one hand and the means of implementation on the other hand; the latter entails inadequate attention to how to transform, beyond global partnerships and international trade, entrenched inequalities and uneven power dynamics that have long been pervading unsustainable development (UNRISD 2016). The climate targets are broad with little in the way of target quantitative measures.

[*Note: perhaps also list targets for Goal 13 here – check with other chapters; or consider as part of a FAQ*]

[END BOX 5.1 HERE]

5.1.3 Climate-resilient Development: Pathways for Transformation

There is much debate about what types of transformative steps are needed for whom, when and where to move toward a sustainable and resilient path, as the 2015 preamble to the SDGs prescribes. What pathway or pathways is/are likely to deliver such a transformative potential, especially in a 1.5 °C warmer world?

The AR5 introduced the notion of '*climate-resilient pathways*', defined as 'sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts; they include iterative processes to ensure that effective risk management can be maintained' (IPCC 2014a: 28). These pathways are best seen as 'future trajectories of development' with a variety of alternative pathways at any possible scale, each of which requires an evaluation of associated risks and benefits regarding climate resilience (Denton et al. 2014). Climate-resilient pathways rely on flexible, innovative, and participative problem solving and, especially in the context of severe effects of climate change, require transformational change, including transformation in social processes (Denton et al. 2014).

Despite high agreement in the literature on the conceptual nature of such pathways, concrete evidence and empirical examples in the AR5 were rather limited. However, since then, the literature on climate resilient pathways and transformation has expanded. It now addresses the efficacy and nature of transformational processes for adaptation and mitigation at the community level, across differing socio-economic and vulnerability contexts and different regions of the world.

With the adoption of the SDGs (Transforming our World: the 2030 Agenda for Sustainable Development), and the fundamental linkages between efforts to achieve both sustainable development and the Paris Agreement, the word 'development' now emerges as an even more fundamental and visible facet, justifying the term 'climate-resilient *development* pathways'. This notion implies deliberate emphasis on understanding how development, transformation, and resilience go hand in hand with efforts to limit global warming, through simultaneous and conscious efforts to reduce vulnerabilities, enhance adaptation, and implement stringent emission reductions.

Furthermore, the foregrounding of transformation in the title of the 2030 Agenda highlights the need to address 'the root causes that generate and reproduce economic, social, political and environmental inequities, not merely their symptoms'; this entails inclusive and rights-based development that offers tangible path-ways to 'break[…] the vicious circle of poverty, inequality and environmental destruction confronting people and the planet' (UNRISD 2016: 3). It stresses the challenge of pursuing sustainable human development against the backdrop of increasing global inequality, future climate change, and current environmental damages (Fleurbaey and Blanchet 2013).

5.1.4 Chapter Structure and Types of Evidence

The chapter proceeds as follows: It first describes what future impacts and risks of a 1.5 °C warmer world are likely to mean for three distinct dimensions of sustainable development, namely poverty eradication, reducing inequalities, and equity, including avoided impacts compared to a 2°C warmer world (Section 5.2). It then discusses how efforts to strive for the various dimensions under the SDGs are likely to affect our global ability to limit warming to 1.5 °C/to reach the 1.5 °C target (Section 5.3). Subsequently, the chapter presents evidence regarding the impacts of action taken to meet the 1.5 °C target (adaptation and mitigation response options) on sustainable development in general and the SDGs specifically, including synergies and trade-offs, across spatial and temporal scales (Section 5.4). Subsequently, the chapter discusses climate-resilient development pathways, examining the foundations needed for such pathways and concrete evidence of climate-resilient development already occurring (Section 5.5). The chapter ends with a brief synthesis of findings and identified gaps, closing the arch of this Special Report that was opened in Chapter1 (Section 5.6).

In this chapter, we use a variety of sources of evidence to assess the interactions of sustainable development broadly and the SDGs in particular with the causes, impacts and responses to climate change of 1.5 °C. We draw upon various types of knowledge and experiences, from measurable data and simulations to lived and embodied experiences of people affected by climate change. We refer to published literature and data that assess, measure, and model sustainable development–climate links from various angles and across scales as well as well documented case studies that illustrate connections, synergies and trade-offs.

5.2 Poverty, Equality, and Equity Implications of a 1.5°C Warmer World

Climate change could lead to significant impacts on extreme poverty by 2030, under both a prosperity scenario and a poverty scenario (Hallegatte et al. 2016a). These future impacts (risks) will be experienced differentially according to caste, gender, or ethnicity within and across societies (Olsson et al. 2014), (Leach 2017). Some of these impacts can be easily detected and attributed to climate change (Cramer et al. 2014) while others are less visible, although no less real to the people who experience them. Drawing attention to these less visible impacts is compounded not only by scarce climate data and other observational records in certain parts of the world (Hansen et al. 2016). It is also compounded by the fact that any global temperature target, including 1.5 °C, is not experienced as such on the ground but will manifest itself in higher warming and/or extreme events in certain parts of the world with highly different patterns of societal vulnerability. This significantly complicates assessing risks of 1.5 °C warming for disadvantaged populations anywhere on the planet. More importantly still, making visible the 'invisible' future impacts and risks is challenging as they entail embodied experiences that emerge at the intersection of systemic inequalities and multi-dimensional vulnerabilities, entrenched marginalization and deprivation, and power asymmetries that are exacerbated by uneven development patters (e.g. Olsson et al. 2014) (Pinho 2016). Therefore, teasing out climate change risk associated with a 1.5 °C warmer world, and beyond, requires a nuanced understanding of intersectional inequalities, and social inclusion and exclusion. Indeed, addressing inequality is at the core of staying within a safe and just space for humanity (Raworth 2012).

This section describes what future impacts and risks of a 1.5 °C warmer world are likely to mean for three distinct dimensions of sustainable development, namely poverty eradication, reducing inequalities, and equity. Understanding such fine-grained impacts and risks that are often difficult to quantify is important because it provides the necessary basis for identifying how the potential for pursuing sustainable development may be curtailed (link to Section 5.3) and how the impacts of adaptation and mitigation response options may further and disproportionally affect already disadvantaged populations (link to Section 5.4), hence constituting possibly double and triple injustices.

This section builds upon findings from the AR5 and Chapter 3 of this Special Report (Sections 3.4 – 3.6: impacts on food security, urban and rural areas, human health, human security, livelihoods and poverty, key economic services, and key vulnerabilities and risks). It highlights the equity and equality implications of impacts and risks associated with a 1.5 °C warmer world that easily escape higher-level analyses and approaches focused on so-called 'hotspots' of climate impacts on human systems. This section adopts the uncertainty language of this SR (see Chapter 1), distinguishing between impacts when referring to observed changes and risk when referring to projected changes.

5.2.1 Risks of 1.5°C and Avoided Impacts of 1.5 °C versus 2 °C

This sub-section explores risks regarding five types of security (livelihood security, human security, food security, water security, and ecosystem security) the treatment of which exceeds the scope of Chapter 3. It assesses a 1.5 °C warmer global reality through projected incremental changes and extreme events for specific places, with an explicit focus on regional, community, household, and individual level (embodied) risks wherever possible. As for avoided impacts, we attempt to highlight nuances that risk remaining invisible when relying exclusively on the Reasons for Concern approach (see Chapter 3, Section 3.6, based on (Oppenheimer et al. 2014).

[*Note: this section will need to be developed in conjunction with Ch3 authors. Ch3 has agreed to populate a preliminary table with possible future impact/risk categories for sustainable development dimensions under 1.5 °C and 2 °C, with emphasis on these five types of security, drawing upon the relevant literature. We will then tease out the more fine-grained risks regarding particular disadvantaged groups, along the axes of intersecting inequalities (see* Olsson et al. 2014).

[*Note: this section will also attempt to tease out poverty, equality, and equity dimensions of anticipated overshoots, building on Ch 3, Section 3.7*]

Table 5.1: Implications of 1.5°C global warming (incremental changes and extreme events) and avoided impacts (1.5°C vs 2°C) for eradicating poverty, reducing inequalities and equity.

[*Note: the table below is illustrative only at this point, but it shows the level of detail we hope to convey*]

Development dimensions	Incremental changes (temperature, rainfall, sealevel rise, glacier melt)	Extreme events (floods, droughts, heatwaves, cyclones)	Avoided impacts (1.5°C vs 2°C)
Livelihood security (assets, incl. health, income, social networks, and livelihood trajectories)	Deteriorating livelihoods and shifts from transient to chronic poverty among marginalized populations in drylands (Xxx et al. 2016)	Heat-related mortality among outside workers, homeless people, the elderly, and children (Xxx 2017)	20% reduction in failed growing seasons in the Sahel and avoided rural-urbam migration (Xxx et al. 2015)
Human security (culture, mobility, migration, displacement, conflict)	Loss of identity and sense of place among indigenous peoples due to sea level rise and glacier melt (e.g. Andes, Pacific Atolls) (Xxx 2012)	Tripling of domestic violence against women in cyclone-prone countries in Australasia, extrapolated from 2010-2016 data (Xxx et al. 2016)	Avoided relocation/displacement among indigenous groups in small-island states in the Pacific and Russian permafrost regions (Xxx 2014)
Food security (food access, food systems)	Widespread abandonment of rain-fed agriculture in India and sub-Saharan Africa in countries without pro-poor climate policies (Xxx 2015)	Increase of urban poor, especially wage labourers, due to increased food prices in East Africa (Xxx et al. 2013)	30% less food insecure people and 25% less extreme poor ($1.25/day) in the Tropics (Xxx 2016)

Given the relatively recent literature on risks for human systems in the context of 1.5 °C, and the challenges outlined above, this section also examines, as a useful proxy, information from the risk tables from AR5 WGII (Intergovernmental Panel on Climate Change 2014) (all chapters, including regions and sectors) in order to extract relevant details with implications for poverty, equality, and equity, comparing Near term (2030-40) which is roughly comparable with 1.5 °C at the end of the century with long-term (2080-2100) 2 °C.

5.2.2 Implications of Differential Risks from 1.5 °C Global Warming for Achieving the SDGs

Intergenerational and distributional concerns arise when vulnerable people face disproportional risks of climate change impacts, whether at different points in time or in different places (Wiess 2017; Shrader-Frechette 2007; Schlosberg and Collins 2014). Since inequality and environmental unsustainability are deeply linked in multiple ways (Leach 2016), it is important to understand how differential risks affect efforts to pursue and achieve sustainable development, particularly when inequalities are expected to further increase and already disadvantaged populations are likely to face even more constrains on their well-being.

This section examines how the potential for making progress in those SDGS directly aligned with poverty eradication and reducing inequalities (SDG1 and SDG10) as well as those indirectly aligned is expected to be curtailed (or enhanced) given the fine-grained impacts examined above. It takes into account the different timelines between the SDGs (2030) and the 1.5 °C target by the end of this century.

[*Note: this section will emerge after 5.2.1 is in good enough shape, which is also conditional on useful and timely input from Ch3. It may draw on particular simulations and/or case studies, extrapolated from current observed impacts. Frameworks that examine SDG target interactions will come in handy here, e.g. PSCD framework by OECD 2016, e,g. showing undesirable synergies between SDGs 5, 10, and 1 – see 5.4.3.2*].

5.3 Sustainable Development and Ambitious Climate Objectives

The adoption of a bottom-up process in Paris[1], led by country decisions on their own pathways, allows for revisiting the role of development considerations in climate policies, given the dominant role played by these development dimensions in decision-making processes. This is particularly true in the context of 1.5 °C-compatible transformations that require a radical shift away from business-as-usual development patterns (Boucher et al. 2016; Griggs et al. 2013).

This new context calls for a re-examination of the conventional framing of development as a co-benefit of climate stabilization in climate change discourse. Indeed, this conventional understanding misses the point that development drives emissions, not vice versa (Winkler et al. 2015; Stern 2007). This section considers climate goals through the lens of development (Kok et al. 2008; Mitchell and Maxwell 2010; Mulugetta and Urban 2010; Stechow et al. 2015; Suckall et al. 2014), and integrates (or 'mainstreams') adaptation into development thinking (Ayers et al. 2014; Saito 2013; Uittenbroek et al. 2013). There is growing literature about the effect of sustainable development on the ability of actors at all levels (from local and sub-national to national and international) to achieve the wide-reaching changes required for a 1.5 °C warmer world.

This section therefore considers the sustainable development dimensions as the entry point of the discussion. It questions to what extent this shift in perspective affects the ability to achieve ambitious emission reductions and enhanced capacities/abilities (lower vulnerability) of populations to climate change. There is

[1]To achieve the Paris climate agreement to hold global warming well below 2 degrees Celsius and to "pursue efforts" to limit it to 1.5 degrees Celsius, signatories agreed to submit Intended Nationally Determined Contributions (INDCs) that outline their post-2020 climate action (Rogelj et al. 2016; Keohane and Victor 2016). Emission reduction contributions are to be "nationally determined" (Art 3 and 4) and each country will have to define its own measures to achieve GHG reductions (Art 4.2). Similarly, adaptation action should follow a "country-driven" approach with a view to integrating it into relevant socioeconomic and environmental policies and actions (Art 7.5).

no agreement in the literature whether pursuing sustainable development facilitates or complicates reaching the 1.5 °C target. No scenario is shown to perform better or worse than others in all dimensions, pointing to inevitable trade-offs between different dimensions of sustainable development (Jakob and Steckel 2016a). The literature is also divided regarding the impacts of a meeting the 1.5 °C target: although the more ambitious emission reductions look unambiguously safer than a 2 °C target when focusing on climate change risks only, the picture may become more complex when comparing the risks of climate change impacts with the costs and co-benefits associated with emissions changes (Hallegatte et al. 2016b).

5.3.1 Achieving Sustainable Development: Impacts on Low Emission Pathways and Adaptive Capacities

The AR4 stressed the two-way relationship between sustainable development and climate change mitigation. Sathaye et al. (2007) concluded that development that is sustainable in many respects can create conditions in which mitigation can be effectively pursued (development first). This is the reverse to the common argument that mitigation can generate co-benefits that foster sustainable development (climate first).

This section starts with a systematic review of the causalities, across sustainable development dimensions, considered one by one. Table 5.2 provides a high-level assessment of how efforts to pursue and achieve the sustainable development dimensions under each SDG effects, first, the likelihood of meeting the 1.5 °C target, through particular choices of low emission pathways (see also Section 5.4, as well as Chapter 2 for a wider discussion) and, second, people's capacities to adapt to a 1.5 °C warmer world. The latter is extrapolated from expected impacts on multidimensional vulnerabilities. The text below provides the accompanying evidence from the literature for each sustainable development category.

[*Note: The table below is illustrative at this point! The text below is evolving with more examples form the literature. There are several options re how to present the more detailed information: either integrated into Table 5.2, or as a box – tbd*]

Table 5.2: Implications of achieving sustainable development (according to the 17 SDGs) for a) the likelihood to meet the 1.5 °C target; and b) human capacities to adapt to a 1.5 °C warmer world. Increase/positive effect (+); decrease/negative effect (-); ambiguous effect (+/-); lack of evidence (0).

Sustainable Development Dimensions	Impact on the likelihood of meeting the 1.5°C target	Impact on the capacity to adapt to 1.5°C
End poverty	+/-	+
End hunger	+/-	+
Ensure healthy lives	+	+
Education for all	+	+
Achieve gender equality	+/-	+
Water and sanitation for all	0	+
Ensure access to affordable, reliable, sustainable and modern energy for all	+	0
Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work	+/-	+
Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	+	+
Reduce inequality within and among countries	+/-	+
Sustainable cities and communities	+	+
Ensure sustainable consumption and production patterns	+/-	+/-
Life below water	+	+
Life on land	+/-	+/-
Peace, justice and strong institutions:	0	+
Partnerships	+	+/-

5.3.1.1 Eliminate poverty goal

Taking people out of poverty increase their access to energy services and hence increases their emissions (REF). But the poverty goal is only about pulling people to a minimum level, perhaps not to a level of wealth where emissions increase (Mugambiwa and Tirivangasi 2017). And it also permits to get access to more efficient technologies which may partially compensate the increase of services (reference).
Taking people out of poverty generally decreases their vulnerability to climate change (reference).
Poverty can decline significantly without necessarily reduction in vulnerability if the households were not investing in risk management strategies (Nelson et al. 2016).

5.3.1.2 Hunger

Increased food security can be associated with higher emissions if it involves land expansion, livestock, high energy use, or it can choose a lower emissions pathway (DeClerck et al. 2016; Rockström et al. 2016)

5.3.1.3 Health

If the health goal involves less air pollution it can increase temperature if reduces pollution (Aitsi-Selmi et al. 2015).
There are common drivers of key sustainable development issues and ambitious mitigation, like coal control for health issues in China in which case the health objective reduces emissions since it means dropping coal and oil (Yang and Teng 2016) combining air pollution control and non-fossil energy target lowers the total cost (Wang et al. 2016).
Moving from polluting stoves to fossil fuel is good for health but maybe not for climate (McDonough 2016).

5.3.1.4 Education

Investment in universal primary and secondary education around the world is the most effective strategy for preparing to cope with the still uncertain dangers associated with future climate (Striessnig et al. 2013).
The central role of education in reducing fatalities due to natural disasters through changes in the total size and the educational composition of each population. (Striessnig and Loichinger 2015).
Highly educated individuals and societies are reported to have better preparedness and response to the disasters, suffered lower negative impacts, and are able to recover faster. This suggests that public investment in empowering people and enhancing human capacity through education can have a positive externality in reducing vulnerability and strengthening adaptive capacity amidst the challenges of a changing climate (Muttarak and Lutz 2014).
Higher skills can be part of a decarbonization strategy if it helps to organize the structural change away from fossil-intensive, low-skills activities (Altieri et al. 2016).

5.3.1.5 Gender equality

Gender equality can mean more consumption, but also surveys on women wanting more aggressive climate policy, gender equality and lower fertility.
Gender mainstreaming is essential in ensuring that not only climate policies and programs are comprehensive, but so too are women-focused policies designed to ensure that women are supported and empowered to take action on their own behalf (Alston 2014).
The prevailing development paradigm reinforces inequitable gender structures in agrobiodiversity management, undermining adaptation to the changing climate (Bhattarai et al. 2015).
Establishing the appropriate connections between gender and climate change will enhance the opportunities for problem-solving and can increase the efficiency and effectiveness of policy-making (Makina and Moyo 2016).
Rural Tanzanian’s adaptive strategies are mediated through their gender and marital status (Van Aelst and Holvoet 2016)

5.3.1.6 Clean water and sanitation

Infrastructure for water on emissions.

5.3.1.7 Affordable and clean energy

There is a direct relationship between 'clean' energy and lower emissions, but providing energy to all can increase emissions, in most countries affordable energy is coal or biomass, coal is easiest for 2030 but in long term its renewables and non-coal.
Sustainable development concerns can be a core motivation to implement deep emission reductions, for example for energy security reasons (Oshiro et al. 2016).
Clean energy potential, obstacles to and stimulants of clean energy implementations, and renewable energy policies in Nigeria (Giwa et al. 2017).

5.3.1.8 Economic growth, and decent work

There is now a growing and extensive literature on growth and the impact of material growth; the challenge of de-coupling growth and emissions. The literature recognizes the tension between achieving GDP growth and significant mitigation and it is particularly developed in the growing literature on de-growth and post growth ecological economics (Shandi et al 2016; Wiseman and Alexander 2017; Jackson 2009; (Weiss and Cattaneo 2017)(Wiseman 2017; Weiss and Cattaneo 2017).
The current development pattern which relies primarily on heavy industry is not sustainable for China's future development. Transformation to an innovative, low-carbon development pattern is needed, in which more attention is paid to the quality, as well as the quantity, of economic growth. This restructuring of growth patterns is aligned with deep decarbonization objectives (Liu et al. 2017)
The reduction of unemployment can be compatible with deep decarbonization pathways in South Africa (Altieri et al. 2016)

5.3.1.9 Industry innovation and infrastructure

Adequate investment in infrastructure consistent with sustainable development objectives decrease the cost of ambitious mitigation and the dependence on high-risk technologies (Shukla et al. 2015).
In the transport sector, they help provide emission reduction potential at a lower cost than with carbon prices (Waisman et al, 2013).

5.3.1.10 Reduced inequalities

Can increase or decrease emissions - literature on GINI coefficients and emissions (Roman and Thiry 2016).
It is possible to reduce inequalities and simultaneously reduce inequalities (Altieri et al. 2016).
However, literature indicates significant global inequality "where 20 of the 36 highest emitting countries are among the least vulnerable to negative impacts of future climate change. Conversely, 11 of the 17 countries with low or moderate GHG emissions, are acutely vulnerable to negative impacts of climate change" (Althor et al. 2016).

5.3.1.11 Sustainable cities

Sustainable cities are usually defined as having lower emissions, but they have very significant embedded/imported emissions and managing sustainability has to consider climate externality impacts (Bank 2010; Pancost 2016).
Integration of climate impacts and urban growth for a large area (Thorne et al. 2017).
Discussion of how cities can contribute to climate change mitigation through an integrated approach involving low carbon development (LCD) as part of a city's strategic planning. Cities have an opportunity to link climate change policies to local developmental priorities (Rescalvo et al. 2013).

5.3.1.12 Responsible consumption to production

Definitions of sustainable consumption and production usually assume lower emissions but we need to consider rebound, and full GHG accounting.

5.3.1.13 Life below water

Protecting oceans requires and enables 1.5 °C, e.g. Blue Carbon.
Kenyan mangroves as a case study in developing Climate-Compatible Development processes of use more generally in coastal management, and a contribution to global debate and practice on Climate-Compatible Development and on valuing 'Blue Carbon' and other coastal ecosystem services (Huxham et al. 2015)
Using the ocean sustainably requires overcoming many formidable challenges, including climate change (Lubchenco et al. 2016).
The ocean provides compelling arguments for rapid reductions in CO_2 emissions and eventually atmospheric CO_2 drawdown. Notably because the ocean strongly influences the climate system and because impacts on key marine and coastal organisms, ecosystems, and services are already detectable, and several will face high risk of impacts well before 2100, even under the low-emissions scenario (RCP2.6). (Magnan et al. 2016; Gattuso et al. 2015).

5.3.1.14 Life on land

Forests and grasslands and peatlands essential to emissions.
Policies and measures to be implemented towards deep decarbonized development, consistent with ambitious climate mitigation for Indonesia, include prominently sustainable management practices in the AFOLU sector, including improving the management of land and forest resources; pushing adoption of sustainable management practices in production forests; reducing dependency on natural forests in meeting wood demands; reducing pressure on natural forest for establishment of development areas and agriculture expansion; enhancing sink by increasing the implementation of restoration of production forests ecosystem and land rehabilitation; limiting the use of peatland for timber and agriculture plantations through the issuance of moratorium policies and peatland restoration (Boer et al. 2016).
But protection could prevent biomass BECCS.
Bioenergy deployment offers significant potential for climate change mitigation, but also carries considerable risks (Creutzig et al. 2015).
Along with afforestation, the production of sustainable bioenergy with carbon capture and storage (BECCS) is explicitly being put forth as an important mitigation option by a majority of Integrated Assessment Model (IAM) scenarios aiming at keeping warming below 2 °C in the IPCC's Fifth Assessment Report (AR5). The deployment of large-scale bioenergy faces biophysical, technical, and social challenges, and CCS is yet to be implemented widely (Fuss et al. 2014; Smith et al. 2016; Anderson and Peters 2016).

5.3.1.15 Peace

Defense emissions, can peace increase emissions? Does peace promote collaboration on climate?

5.3.1.16 Partnerships

Most important is the flow of finance and technology to reduce emissions, partnerships with non-nation state actors e.g. cities and local communities is important (Anderson 2017).
This is actually the logics of the Paris Agreement which emphasizes the need for collaboration among actors as the mean to reach ambition global mitigation and adaptation goals.

5.3.2 Multidirectional Interplays

The analysis provided in the previous section ignores three key dimensions that need to be taken into account when investigating the link between sustainable development and climate change. [*Note: this can be better* *linked with the discussion in 5.4*]

First, a key challenge lies in the cross-sectoral nature and complex interlinkages between the sustainable development dimensions; these need to be captured through policy integration (Boas et al. 2016; Dimitrov 2016). This body of literature addresses connections between climate, food, energy and water, and other development dimensions (Rasul and Sharma 2016; Conway et al. 2015; Welsch et al. 2014). There is also increasing recognition that a reductive focus on specific sustainable development goals in isolation may undermine the achievement of sustainable climate change mitigation (Holden et al. 2016).

Second, the interplays between the sustainable development dimensions and climate change depend largely upon the context in which these interplays occur. This context then defines the specific approach to the generic sustainable development dimension. For example, in Least Developed Countries, reducing negative health effects may be achieved through the deployment of modern cook stoves replacing traditional ones, which, however, can increase emissions (at least temporarily). When considering outdoor air pollution caused notably by the use of fossil fuels, which is a major aspect of health effects in many developing and emerging economies, the convergence between the health objective and mitigation policies becomes clear. Howell (2013) shows that people adopt low-carbon lifestyles for reasons that extend beyond a desire to merely reduce greenhouse gas emissions, including values such as equality, social justice, and unity with nature.

Third, the time dimension plays a key role in the nature of the interplays as they are not static in nature but rather evolve over time. The key issue is the articulation of timings inherent to the different sustainability processes (Chang et al. 2017; Turnheim et al. 2015). The backcasting approach starting from a desired development and climate objective and designing the trajectories suited to lead from the current situation to the desired objective (Bataille et al. 2016) helps to go beyond the 2030 horizon of the SDGs, but enables to see interim transformations in the light of the opportunities and/or obstacles they create for the long-term transformation required by the 1.5 °C climate goal. [*see discussion in 5.4.3*]

5.4 Impacts of Adaptation and Mitigation Response Options on Sustainable Development: Distribution, Synergies and Trade-offs

This section examines interlinkages between climate response options, sustainable development, and the SDGs. There are synergies and trade-offs between the two aspirational goals of 1.5 °C and sustainable development, with SDGs as interim goals depending on the sector and region. There are likely to be many response options that are consistent with achieving the 1.5 °C target by 2100. However, not all response options will be optimal with regards to their capacity to ensure that other non-climate SDGs are met, at specific points in time. A detailed understanding of the various synergies and trade-offs associated with the pursuit of interrelated climate and SDGs is important, especially for designing alternative, corrective, scaling up of measures. Articulating sustainable development and adaptation and mitigation objectives opens windows of opportunities to reach efficiency, sustainability, and optimality in each specific context. Simultaneously considering sustainable development, adaptation and mitigation strategies, and response options allows policy makers and practitioners to better understand the various linkages and identify efficient and socially desirable outcomes, to pursue their own priorities and work toward outcomes that are most beneficial for the global community, including non-human species and future generations. It also allows for highlighting of potential pitfalls that potentially undermine sustainable development, equity, and justice.

[*Note: The main instrument for the analysis in sections 5.4.1 and 5.4.2 are the two tables – one table in each section. The table is a matrix between the 16 SD dimensions and sectoral adaption measures (in 5.4.1) and mitigation measures (in 5.4.2). These tables will be populated with information on impacts (and the confidence of each finding) of each adaptation/mitigation measure on the SD dimension in question. The idea and structure of these tables is close to the AR5 WGIII table 6.7 (pages 469-471).*]

5.4.1 Climate Adaptation Options

The impacts of adaptation measures on sustainable development in general and the SDGs specifically will likely be largely positive, given that the inherent purpose of adaptation options is to decrease exposure and vulnerability, facilitate incremental and transformative adjustment, and foster transformation (IPCC, 2014a), see Table 1). However, certain adaptation options are likely to cause negative side-effects, particularly for poor and vulnerable populations and with respect to various dimensions of equity and equality.

This section comprises two parts. The first part provides a brief overview of adaptation-SDG synergies, focusing on core areas of reduced risks and enhanced adaptive capacities. The second part systematically assesses potential negative trade-offs between specific adaptation options and SD dimensions and/or targets. This section calls for a more in-depth investigation of so far often overlooked negative impacts and side effects.

5.4.1.1 Synergies between Adaptation Options and Sustainable Development

The highly diverse adaptation options across sectors, individuals, communities, and locations perpetuate the challenge in evaluating adaptation measures. These constraints have been discussed in AR5, e.g. Chapter 14 notes that the most common adaptive responses are still engineered and technological strategies although recognition for ecosystem-based, institutional and social measures has been increasing (*robust evidence, high agreement*) (Noble et al. 2014). Streamlining adaptation options into policy frameworks, private sector action, and institutional thinking can ensure better fit with core objectives of development planning and reduce risks of maladaptation (Noble et al. 2014). Failing to take into account the long-term impacts of adaptation actions may also lead to maladaptation. For instance, building seawalls increases the number of populations at risk by encouraging development in low-lying areas (McGranahan et al. 2007).

Evaluating the impacts of adaptation options on sustainable development is further compounded by the fact that these options are often designed not only to reduce climate risks and enhance opportunities but also to address broader societal goals such as poverty reduction, providing employment, and enhancing the resilience of complex social-ecological systems. Gains in reduced vulnerability, enhanced resilience, or greater welfare will often be co-benefits generated as a result of changes and innovations driven by other factors (Khan et al., 2013).

[*Note: this section will review the literature on (expected and observed) co-benefits, focusing on the middle section of approaches to managing risk in Table TS7 (AR5 WGII), namely incremental and transformational adjustments (adaptation) and their impacts on sustainable development*]

However, not all adaptation options produce just synergies, or negative side effects. Such a two-way relationship, for example, is well established in the field of public health. On the one hand, effective adaptation measures for the near-term, in situations where basic needs are yet to be met, or resources are scarce, are programs that implement basic public health measures (Dasgupta 2016; Hess et al. 2012), (Smith et al. 2014). Adaptation needs are linked with existing adaptation deficits. Examples of where measures to reduce current adaptation deficits are important for tackling future climate change impacts (Woodward et al. 2011). On the other hand, specific and planned adaptation efforts are required in parallel for climatic events, such as recurrent flooding. This, however, can lead to erosion of household coping capacity over time (Webster and Jian 2011), damage to infrastructure, undermining of long-term adaptive capacity, and increases in cumulative risk (Tapsell et al. 2002). In this case, more of the same is not sufficient.

Sectoral and regional aspects require special attention. There is a dearth of studies that analyze the processes or effectiveness of adaptation actions. For instance, studies on climate change impacts on water quality and adaptation to these are required especially for developing countries (AR5 WGII Chapter 3). These have a direct bearing on adaptation responses for climate-resilient ways of meeting SDG goals. At the same time, sectoral mitigation and adaptation actions can also have unintended consequences for other sectors, though these risks may have not been adequately assessed (AR5 WGII Chapter 19). An important aspect of climate change response policy is the ability to utilize the effectiveness of social norms in promoting adaptation and explicitly consider the challenges faced by developing countries in dealing with risk and uncertainty (AR5 WGII Chapter 1). Case studies and documentation of effectiveness of actions taken are required to understand the determinants and regional variability of exposure and adaptive capacity (AR5 WGII Chapter 21). Case studies on adaptation turning points (e.g. the reintroduction of salmon and the disappearance of mud flats due to sea level rise) contribute to this understanding (Werners et al. 2015).

5.4.1.2 Negative Trade-offs between Adaptation Options and Sustainable Development

Table 5.3 below is based upon Table SPM.1, WGII AR5. Specific response options are listed with their category details. A description of the negative trade-off is provided and supporting literature referenced. The quality of the supporting literature is assessed following IPCC uncertainty guidelines.

Table 5.3: Negative impacts of adaptation response options on sustainable development/SDGs. The categories are based upon Table SPM 1 (AR5, WGII, p96)

Adaptation Response Option	Category	Sub-Category	Position on Adpatation Spectrum	Negative Impacts on SD Dimensions	SDG Target	Supporting Literature	Evidence	Agreement	Confidence
Integrated Coastal Zone Management	Institutional	National and Government Policies and Programs	Incremental/ transformational adjustments	Displacement from coastal settlements	1.4; 11.3	Xxx et al. (2017), Xxx et al. (2014)	Medium	High	Medium
				Exclusion of small-scale fishers and indigenous peoples from traditional fishing zones	2.1; 11.4	Xxx et al. (2015), Xxx et al. (2016)	Robust	Medium	High

[*Note: this table is under development. It illustrates how we intend to review the literature for this section*]. [*Note: It would be interesting to explore here how certain overshoot scenarios may make a difference for the choice of adaptation options, e.g. fast and massive use of structural/engineering options at the cost of 'softer' social-institutional adaptation, e.g. social safety and community-based adaptation*.]

5.4.2 Climate Mitigation Options

In the AR5 WGIII, many mitigation options across sectors have been identified by the scientific community that can deliver short as well as long term climate goals with multiple benefits but some have additional cost implications in terms of other societal and economic goals. These cost implications vary over time and space. In this section we augment the AR5 knowledge with new information corresponding to various SD dimensions and SDGs in particular and with new stringent climate goal. Aligning mitigation actions to overall sustainable developmental objectives needs attention to ensure public acceptance (IPCC WGIII 2014) and to enable policy design to ensure fast actions (Lechtenboehmer and Knoop 2017).

5.4.2.1 Synergies between Mitigation Options and Sustainable Development

There is high agreement in the literature that pursuing stringent climate mitigation options generates positive non-climate co- benefits that have the potential of reducing costs of achieving multiple dimensions of sustainable development (Schaeffer et al. 2015b; Ürge-Vorsatz et al. 2014; Stechow et al. 2015; Singh et al. 2010; Ürge-Vorsatz et al. 2016) (IPCC WGIII, 2014).

Cities across the world have been identified as important climate actors, also in the Paris Agreement, yet the opportunities and challenges vary immensely depending on their rate of population growth, geography and climate, urban morphology, sociocultural aspirations, governance capabilities, and success in sustaining existing businesses and attracting new investments (Colenbrander et al. 2016). Cities are facing sustainability challenges from multiple angles, including air pollution, access to affordable services like health, water, housing, and energy with ever growing population pressures from natural and migration related growth. Being major growth centers, innovation in technology and policy design is aiming to achieve both low carbon growth strategies and local priorities in building construction materials choice, energy efficient appliance standards, new industrial product design, and infrastructure designs.

Identification of mitigation options with positive impacts on sustainable development may not be sufficient to deliver desired sustainable development objectives unless they are rightly valued and integrated into policy packages, supplemented by governance coordination across sectors and nations (Stechow et al. 2015), and ensure collaboration and dialogue between local communities and municipal bodies, e.g. in megacities (Colenbrander et al. 2016; Gosh et al. 2016). In fast devloping countries, efforts need to go beyond green growth indicators (Roy et al. 2016).

[*Note: this sub-section and the next will review the existing literature more extensively across sectors and regions and will populate the table and intend to add texts to help easy identification of options with SD implications and enabling policies.*].

5.4.2.2 Negative Trade-offs between Mitigation Options and Sustainable Development

Deep cuts to emissions could impede development for certain regions, countries, and populations unless low carbon pathways and low cost energy are rapidly made available and implemented. In many megacities in low- and lower-middle income countries, climate mitigation is typically a secondary consideration . Many mitigation options pursued independently can lead to loss of livelihoods (Colenbrander et al. 2016).

The cost of limiting warming to 1.5 °C above pre-industrial levels are high and not evenly distributed (Schaeffer et al. 2017). They could divert resources needed for sustainable development if no additional funding is available.

Impacts of carbon mitigation policies in the UK (Gough 2011): policies highly regressive; higher share of spending in lower income households; these cost increases cannot be addressed via social benefits, tax allowances and credits; additional policies would be needed (eg ‘social’ energy tariffs, but these might compete with existing state social expenditures in times of fiscal stringency [*point here: negative impacts on poor people in HICs*]

Table 5.4: Impacts of mitigation options on specific targets of the 17 SDGs

SDG	Target Category	Mitigation Option: BECCS					
		Supporting Literature	Interactions Identified	Score	Evidence	Agreement	Confidence
1 (No Poverty)	Poverty and Development (1.1/1.2/1.3/1.4)	Smith et al. (2016), Xxx et al. (2013), Xxx et al. (2015)	Creates new market opportunities and sources of income for poor, though impacts on poverty and development highly region-specific	[+1, 2]	Robust	Medium	High
		Xxx et al. (2014)	Increases price of staple food prices with disportional impacts upon people living in extreme poverty	[-2]	Robust	High	High
	Exposure and Vulnerability (1.5)	Smith et al. (2016), Xxx et al. (2017)	Potential to enhance local adaptive capacity via increased local income, though this is contigent upon means of implementation	[0, +1]	Robust	Medium	Medium
2 (No Hunger)	Food Security and Agricultural Productivity (2.1/2.4)	Smith et al. (2016), Muratori et al. (2016)	Land requirements for BECCS competes with space for food crops, increasing land and food prices	[-2]	High	High	Very High
	Farm Employment and Income (2.3)	Muratori et al. (2016)	Creates local employment opportunities centred upon bioenergy production	[0, +1}	Low	Low	Low
3 (Good Health and Well-Being)	Disease and Mortaility (3.1/3.2/3.3/3.4)	Xxx et al. (2014)	Large-scale land clearing for bioenergy crops reduces certain disease risks and alters tropical disease vectors	[0, +1]	Low	High	Medium
	Non-communicable Disease (3.4/3.6)	Xxx et al. (2015)	Increased food prices reduce food security and drive malnurution and its related diseases	[-1, 2]	Medium	High	High
	Health Care Provision (3.7/3.8)	-	-	-	-	-	-
	Air Pollution (3.9)	Xxx et al. (2015), Xxx (2017)	Improves local air quality	[+2}	High	High	Very High

[Note: at this point, the table is illustrative. It shows only one example, BECCS, although there are of course many mitigation options to evaluate cross sectors. This table layout might change and could be combined with a sectoral design, see AR5 WGIII categories, Table 6.7, p469*). The goal now is merely to show how we are planning to comprehensively assess the literature on mitigation options and SD dimensions and uncertainty statements]*

5.4.3 Synergies and Trade-Offs Between Response Options over Time and Space

This section examines how synergies and trade-offs may occur among various climate response options and other non-climate sustainable development policy objectives, taking into account differences in distribution over space and time. The findings will set the stage for the final section (Section 5.5) that describes which climate-resilient development pathways emerge for which countries/regions/communities and at what stages of a development trajectory.

Core messages of this section:

- There are synergies and trade-offs between the various options proposed to limit global warming to at 1.5 °C, their impacts, and achieving the SDGs. These synergies and trade-offs will vary depending on sectors, regions, stages on development trajectories, and social values and preferences.
- Adaptation and mitigation strategies typically operate at different spatial and temporal scales, which makes efforts to identify interactions a challenging task. Adaptation tends to occur at lower spatial levels (particular household, community, and city levels) while mitigation action is often driven by national, regional, and global policies and technological advances (e.g. countries that adopt or reject nuclear power). Consumer behavior and individual lifestyle choices are mostly driven by dominant worldviews within a society (see O'Brien's work). Action taken at one scale may well affect actions taken at another scale (cross-level and cross-scalar interactions, including mismatches).
- The costs of adaptation at or above 1.5 °C are high and could divert resources from development if additional financing is not available.
- The costs of limiting warming to 1.5 °C are high and not evenly distributed. They could divert resources needed for sustainable development if no additional funding is available.
- Risks of maladaptation are expected to increase as a result of inadequate integration between adaptation and mitigation policies and approaches. This includes adaptation options being foreclosed as a result of a narrow focus on mitigation, particularly for poor people and those experiencing multiple stresses on their livelihoods, in different regions of the world.
- Synergies and trade-offs, including unevenly distributed benefits and risks, also occur in green economy approaches; improved human well-being and social equity do not automatically arise. Negative impacts from environmental and climate policies under the umbrella of greening economies have reinforced existing inequalities and injustices.

It is both a challenge and opportunity, particularly for fast growing economies, to strike a strategic balance between fast-paced economic growth, structural shift of the economy, and social development without being on a high GHG emissions pathway. At the same time, all countries in different states of development have pressing adaptation needs that require substantial investment and scaling up.

AR5 identified sources of tradeoffs - how adaptation options could lead to additional emissions (IPCC 2014 Ch 10 WGIII, e.g., Production of mitigation technologies (e.g., insulation materials for buildings) or material demand for adaptation measures (e.g., infrastructure materials) contribute to industrial GHG emissions) but there was no comprehensive assessment of these trade off and synergic effects. [*Note: Similar examples will be included from other findings from the AR5*]

5.4.3.1 Temporal, Spatial, and Social Trade-offs of Adaptation-Mitigation Interactions

5.4.3.1.1 Temporal dimensions

Delaying action to reduce greenhouse gas emissions increases the risks associated with mitigation [*high* *confidence*]. Weak mitigation targets in the short term necessitate significant and rapid upscaling of mitigation efforts in the medium term, with associated increases in mitigation costs and risks. For instance, deferral of comprehensive global emissions reductions produces higher costs for achieving a given climate target, while also reducing the likelihood of being able to achieve more stringent climate targets (Luderer et al. 2013; Schaeffer et al. 2015a). Delayed stringent mitigation in the near term increases that rate of transition to low greenhouse gas emission technologies required to achieve 450 ppm CO_2e (Eom et al. 2015). Faster transitions increase the risks of stranded investments in coal capacity (Johnson et al. 2015) and associated job losses (Rozenberg et al. 2014), as well as the risks associated with grid integration of fluctuating renewable energy (Stechow et al. 2016). Examining the linkages between mitigation options and energy-related SDGs (Stechow et al. 2016) revealed that delayed mitigation (coupled with constrained mitigation technology) reduces flexibility of future response options, while also lowering synergies and increasing negative trade-offs across environmental and socioeconomic objectives. Weak mitigation in the short term also necessitates increased deployment of 'negative emission technologies' in the medium term (Bertram et al. 2015; Luderer et al. 2013). Although considered essential to achieving the 1.5 °C target (Rogelj et al. 2015), negative emission technologies carry significant technological and economic uncertainties, as well as various potential impacts upon land, energy, water and nutrient systems (see, for example, Smith et al. 2016).

Constraining technological options for mitigation increases overall mitigation risks [*high confidence*]. This is because constraining technological options only reduce risks associated with that specific technology (Stechow et al. 2016), whilst requiring other technological options to be scaled up. For example, constraining BECCS may mean up-scaling nuclear energy options, thus increasing risks associated with nuclear proliferation and nuclear waste (Stechow et al. 2016; Muratori et al. 2016). Furthermore, restricted technological portfolios have higher associated financial costs than unconstrained technological portfolios (see, for example, Luderer et al. 2013; Jakob and Steckel 2016).

Mitigation responses are likely to produce differentiated opportunities and risks in the context of sustainable development when descaled to the regional/nation/local level. This is because social, economic, environmental and political contexts shape how mitigation opportunities and risks and costs manifest in specific places. For instance, the costs of mitigation vary significantly between regions, with aggregate relative costs typically lower in OECD and Latin American countries and higher in other regions (Clarke et al. 2014). Emission reduction costs associated with Nationally Determined Contributions (NDCs) also differ significantly between countries as a percentage of GDP (Akimoto et al. 2016).

5.4.3.1.2 Regional differences

Future climate response options are expected to continue to impose differential regional impacts. For example, economies that are highly dependent upon fossil fuel-based energy generation and/or export revenue are likely to be disproportionally impacted by future efforts to restrict the use of fossil fuels, resulting in stranded assets and unusable resources (Johnson et al. 2015; McGlade and Ekins 2015). In turn, different climate response options will likely have regionally-differentiated implications for energy and food security. Cumulative oil imports as a percentage of oil consumption are projected to rise significantly for Asian and OECD nations under mitigation scenarios consistent with the 2 °C warming target (Jakob and Steckel, 2016). Alternatively, technological constrains are projected to significantly alter global energy trade patterns out to 2100 under 'full technology' and 'no CCS' scenarios (Muratori et al. 2016). Under the latter scenario, fossil fuels are virtually no longer used by 2100, resulting in many Middle Eastern and African energy exporters becoming net energy importers by the end of the century while many North American and Eastern European nations become net exporters. The large-scale deployment of bioenergy also has significant regionally-diffuse implications for land use and food prices, with the linkages between biofuel production, transnational large-scale land acquisitions, food prices, land dispossession and their disproportionate impacts upon rural poor and indigenous populations well documented within the literature (e.g. Olsson et al. 2014; Aha and Ayitey 2017; Johansson et al. 2016).

5.4.3.1.3 Scalar disconnects

Climate response options can also impact adaptation efforts at other scales. Adaptive responses are often initially reactive and opportunistic and, hence, may not align with development and/or mitigation strategies developed at higher governance levels; this can lead to a 'mitigation-adaptation disconnect' in which proactive mitigation policies enacted at one level constrain or cancel out adaptive efforts at another (Thornton and Comberti 2013). Such a situation may be particularly problematic if mitigation strategies narrow the range of adaptive options available to local communities or regions, producing potentially mal-adaptive responses that further exacerbate local and regional vulnerabilities. In turn, maladaptive responses may undermine mitigation efforts conducted as local scales.

5.4.3.1.4 Social pitfalls and justice traps

Critical analyses of green economy approaches have revealed inadequate incorporation of social dynamics into sustainable development, resulting in a potential 'triple injustice' that reproduces and/or exacerbates negative impacts from climate-focused policies and, hence, inequalities, particularly among disadvantaged and marginalized groups (Cook et al. 2012; UNRISD 2016). Green technologies tend to favor high-income countries who have the means to invest in structural transformations, benefit from economic opportunities associated with adaptation and mitigation policies, and absorb the costs of negative side-effects (UNRISD 2016) as well as urban populations to the detriment of the rural poor (e.g. Hezri and Ghazali 2012). More specifically, unjust and adverse effects have been documented for biofuel (various African countries, India, Indonesia) and hydropower projects (e.g. State of Sikkim, India), predominantly through displacement and replacement of subsistence food economies, resulting in increased food insecurity and reduced access to fuel for the rural poor. Even in countries of the Global North, low-income populations are often left out of renewable energy generation schemes, either because of high start-up costs or lack of home ownership (UNRISD 2016), while conservation efforts to enhance land and forest carbon sinks have excluded traditional owners and indigenous populations from efforts to manage natural resources, as in the case of Australia (Winer et al. 2012). Hence, trade-offs between SDG 7 (promoting renewable energy production) and other environmental efforts (SDG 15) need to be scrutinized for impacts on social aspects, particularly access to land embedded in SDGs 1 and 2.

5.4.3.2 Interactions between the Sustainable Development Goals (SDGs) and their Targets

It is increasingly recognized that not all SDGS and their associated targets are likely to support one another, despite the claim that the SDGs are considered indivisible. Tension, conflict, and negative trade-offs exist between some goals and targets while several goals and targets reinforce each other and are best tackled in integrated ways (LeBlanc 2015) (Nilsson et al. 2016b; ICSU and ISSC 2015). Lessons from the 'nexus' approach is demonstrative the need to navigate synergies and negative trade-offs in the context of multi-objective decision making (Nilsson et al. 2016). Policy coherence implies not only better coordination in implementing SDG interventions and matching the global level goals and targets with national agendas; it also implies ensuring that technological efforts and macro-economic policies don't undermine welfare and sustainability priorities (UNRISD 2016).

In order to assess how climate change response options affect sustainable development in general and the SDGs specifically, it is essential to first understand how the SDGs influence each other as to conceptualize how adaptation and mitigation options impact these linkages and 'filter through' the web of sustainable development dimensions, both directly and indirectly.

[*Note: below we present two frameworks to simply help us think about how we can best address the more complex synergies and trade-offs in the next sub-section*].

Developing frameworks capable of conceptualizing SDG interactions is a nascent effort. Two frameworks are described here as useful examples. First, the OECD (2016) formulated a new approach to promote 'policy coherence of sustainable development' (PCSD) as a strategic response to the SDGs. The PSCD framework offers general guidance and a screening tool (checklist) to identify policy coherence (analytical framework), align existing institutional mechanisms for policy coherence (institutional framework), and consider key elements for tracking progress on PCSD (monitoring framework). It includes a visual representation of three types of target interactions (synergies, trade-offs and enablers) in tabulated form.

Second, Nilsson et al. (2016a,b) offer an alternative framework for analyzing SDG interactions (ICSU 2016).

Their ordinal scale encompasses seven possible interactions, ranging from the most positive (+3) through to the most negative (-3). 'Positive' scores represent synergistic interlinkages between sustainable policy objectives, whereas 'negative' scores indicate negative trade-offs. The scale can be applied to any level of the SDGs – goals, targets and indicators. The framework can be used to analyze how achieving a certain target will affect other policy areas, or how a certain intervention will alter different targets and goals.

5.4.3.3 Impacts of Climate Response Options on SDGs

This section identifies which response options to limit warming to 1.5 °C maximize synergies and minimize negative trade-offs between the various SGD goals and targets. It also draws upon key findings from other chapters of the report, assessing how climate risks associated with 1.5 °C warming (Chapter 3) and various climate response options (Chapters 2 and 4) affect SDG linkages. The findings will be linked to the discussion of climate-resilient development pathways (5.5).

[*Note: this section will deliver a 'master matrix' of the most significant synergies and trade-offs for several climate-response options, supported by a detailed table with all relevant literature. Ideally, the findings ought to be presented in compelling figures, highlighting regional differences, supported by 2-3 case studies (e.g. in a box) that flash out characteristics of differential impacts. Figure 5.1 provides an example of how such an illustration could look like. McCollum et al. (under review) show how the different kinds of energy solutions encapsulated in SDG 7 (Energy) result in impacts on other SDG objectives, and vice versa (preliminary), using the scoring system by Nilsson et al. (2016a)*].

[INSERT FIGURE 5.1 HERE]

Figure 5.1: Nature of the positive (green) and negative (red) interactions between SDG 7 (Energy) and the 16 non-energy SDGs (Source: McCollum et al. Under Review).

[*Note: Another (complementary) option is to illustrate interactions across levels and scales, as shown in Figure 5.2. This approach could be used to convey case study dynamics. Different adaptation and mitigation response options emerge at distinct levels of the spatial scale: the community level (bottom), national institutions, laws, policies, ministries etc. (intermediary level) and the global level (top). There are interactions between players at the same level, and some interactions across levels, as well as some non-interactions, perhaps even mismatches. In essence, how is climate-resilient development on the ground connected horizontally and vertically? Where are the linkages and where are the challenges/mismatches?]*

[INSERT FIGURE 5.2 HERE]

Figure 5.2: Schematic illustration of scalar interactions (Source: Bahu et al. 2013).

5.5 Climate-Resilient Development Pathways

The previous section discussed impacts of adaptation and mitigation response options on sustainable development dimensions and goals, in a largely descriptive and static way. This section adopts a distinctly more dynamic perspective, approaching options for the future from a pathway perspective, at various spatial and temporal scales. Such pathways are likely to consist of a 'collective of alternative choices' (Denton et al. 2014) with distinct benefits, costs, potentials and limitations. One of the strengths of such a pathway approach is that decision making regarding these choices is often more inclusive and equitable. Therefore, it would be misleading to assume that emission reduction and transition pathways that demonstrate the highest number of synergies are necessarily synonymous with climate-resilient development pathways. Equally misleading would be to uncritically equate efficient climate risk management and climate-resilient development that echoes the 2030 Agenda's call to transform our world.

The terms *resilience* and *transformation*, at times used rather loosely or even interchangeably, both denote possible pathways consistent with just and sustainable development. Despite distinct disciplinary origins and wide-spread scholarly debates, these two terms stress the need to do things differently in order to achieve radically different and urgently needed outcomes when facing climate change and other global challenges

(UNRISD 2016). Social-ecological resilience, in particular, promotes space for innovation, experimentation, and collective learning (e.g. Folke 2006) while also acknowledging the politics that surround people's resourcefulness as a core element of environmental governance (e.g MacKinnon and Derickson 2013).

The 2030 Agenda explicitly addresses resilience in SDG 13 (climate action, target 13.1 – 'Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries') as well as five other SDGs: poverty (1.5), hunger (2.4), industry, innovation and infrastructure (9.1), sustainable cities and communities (11 – resilient cities), and life below water (14.2). Climate resilience also overlaps with gender equality (target 5.4 unpaid and domestic care work), for instance in climate-resilient und sustainable agriculture (Kanengoni 2015).

The AR5 conceptualized such climate-resilient pathways as embedded within an opportunity space dotted with multiple decision points; at each critical junction, choices would lead to possible futures along a spectrum from high resilience and low risk to low resilience and high risk (see Box 5.2 Figure 1b). Ch20 noted that climate-resilient pathways require strong institutions to "create an enabling environment through which adaptive and mitigative capacities can be built" and "foster innovation, monitoring, and evaluation of strategies for managing climate impacts and reducing risks" (Denton et al. 2014:1119). This goes beyond identifying and implementing mixes of technological and governance options that reduce net emissions and at the same time support sustainable economic and social growth (Denton et al. 2014).

This section scrutinizes 'best' emission reduction pathways (least trade-offs or negative side effects) for their transformative potential, with explicit attention to the dimensions of equity, fairness, and justice. It makes visible possible tensions between 'economically and technically optimal' pathways and 'socially desirable and acceptable' pathways, acknowledging that the former may increase rather than decrease risks for already disadvantaged populations (von Stechow et al. 2016). Identifying socially acceptable 1.5 °C pathways goes hand in hand with framing climate policy in a broader sustainable development context. The section is structured as follows: it first examines the differential synergies (co-benefits) and trade-offs between emission pathways toward a 1.5 °C target and a 2 °C target, applied with explicit emphasis to sustainable development dimensions; it then evaluates these pathways in the context of the transformative agenda laid out in the SDGs, anchored in just and sustainable climate-resilient development.

5.5.1 Differential Synergies and Trade-offs between Climate/Emission Pathways, with Implications for Sustainable Development

This sub-section summarizes insights from the literature on emission/GHG reduction pathways toward 1.5 °C and 2 °C (including some key underlying mitigation options) and their differential synergies and trade-offs, with respect to their implications for various sustainable development dimensions. These include air pollution and health, food security & hunger, energy access, biodiversity, water security, and poverty and equity (see Sections 5.3 and 5.4). The pathways are assessed with respect to possible positive as well as negative side-effects leading to either synergies (co-benefits) or trade-offs between climate mitigation/adaptation and sustainable development.

Building also on findings from Chapter 2, we draw upon comparative and multi-model studies, which help to identify robust conclusions, as well as multi-regional studies, which can be aggregated to the global scale. Emphasis is on pathways depicting fundamental transformations and thus stringent mitigation policies consistent with 1.5 °C and 2 °C. Wherever possible we discuss also near-term implications in terms of the INDCs and SDGs.

[Note: Studies that explore SD-climate policy linkages of mitigation and adaptation pathways, such as CD-LINKS (http://www.cd-links.org), are still in preparation. This section is thus preliminary and will require a fundamental update once the expected multimodel results become available]

5.5.1.1 Air pollution and health

Greenhouse gas and air pollutant emissions typically derive from the same sources, such as power plants, factories, and cars. Hence, mitigation strategies that reduce the use of fossil fuels typically result in major cuts in emissions of black carbon (BC), sulfur dioxide (SO2), nitrogen oxides (NOx), and mercury (Hg), among other harmful species (Clarke et al. 2014, see Section 5.3), causing a variety of detrimental health and ecosystem effects at various scales (see Barker et al., 2007; Bollen et al., 2009b; Markandya et al., 2009; Smith et al., 2009; Sathaye et al., 2011; GEA, 2012).

Mitigation pathways typically show that there are significant synergies for air pollution, and that the synergies increase with the stringency of the mitigation policies (Rao et al, 2016). Recent multimodel comparisons indicate that GHG reduction pathways consistent with 1.5 °C would result in considerably higher co-benefits for air pollution and health compared to pathways that stay below 2 °C (Krey et al, forthcoming). The co-benefits for air pollution are the biggest in the developing world, particularly in Asia (see panel a, Figure 5.3 below). The currently pledged NDCs lead in most countries to limited structural changes only. Hence, the co-benefits for air pollution is relatively small if compared to mitigation strategies consistent with 2 °C and below (see panel a, Figure 5.3 below).

5.5.1.2 Food security and hunger

Stringent climate mitigation strategies in line with ‘well below 2 °C’ or ‘1.5 °C’ goals can rely on the deployment of large-scale land-related measures, like afforestation or bioenergy production (Rose et al, 2013, Popp et al, 2014). These measures can compete with food production and hence raise food security concerns (Smith et al, 2015). Mitigation studies indicate that so-called “single-minded” climate policy, aiming solely at limiting warming to 1.5 °C or 2 °C, can have negative impacts for global food security (Fujimori et al, forthcoming). Impacts of 1.5 °C mitigation pathways can be significantly higher than those of 2 °C pathways (see Figure 5.3 below), particularly in Africa and parts of Asia. In these scenarios, mitigation policies worsen food security by more than doubling the number of people at risk of hunger in 2050 compared to a case without climate mitigation.

In order to avoid food-security trade-offs mitigation policies need to be designed in a way so that they shield the population at risk of hunger from possible negative food price effects. Fujimori et al (forthcoming) find that such policies can entirely eradicate the identified trade-off between climate mitigation and food security. The cost measured by welfare changes for these food security policy options are found to be low globally and significantly smaller than the mitigation costs of 2 to 6% that are associated with 1.5 °C pathways (Rogelj et al, forthcoming).

5.5.1.3 Lack of energy access / energy poverty

A lack of access to clean and affordable energy (especially for cooking) is a major policy concern in many countries, especially in South Asia where over 70% of the population relies primarily on solid fuels for cooking even today (GEA, 2012, IEA &WB 2015). This has far reaching effects on health and wellbeing, in particular for the most marginalized including women and young children (Pachauri et al, 2012).
Studies that quantify interactions between climate mitigation and energy access indicate that adverse side-effects of climate policies could significantly slow down the transition to clean cooking fuels (Cameron et al, 2015). Increasing the stringency of mitigation policies has generally a diminishing effect on emissions, but also an increasingly negative effect on energy access to clean cooking. For example, under stringent mitigation pathways (e.g., 2 °C Climate Policy Scenario), there could be up to 20% additional solid fuel users in South Asia in 2030 compared to *Current Policies* without stringent mitigation (see Figure 5.3 below). Perhaps most importantly, studies that explored whether the trade-offs between energy access and climate policies can be resolved, indicate the redistribution measures such as subsidies on cleaner fuels and stoves could more than offset the negative effects of rising energy fuel costs for the poor spurred by climate policy. Within this context, climate policy might potentially act as a means to finance energy access policy costs (Cameron et al, 2016).

[*Note: At the moment primarily focused on clean cooking and results from Cameron et al. An entire 1.5 °C model comparison on this topic is under way, and thus we’ll need to update the section later. Can add also some discussion on electricity access to the next draft*]

5.5.1.4 Water security (energy-related)

Transformations towards low carbon energy and agricultural systems can have major implications on freshwater withdrawal and pollution. The up-scaling of renewables and energy efficiency as depicted by low emissions pathways will, in most instances, reinforce targets related to water access, scarcity and management by lowering water demands for thermal cooling at energy production facilities ('water-for-energy'), compared to less-efficient fossil energy technologies. However, bioenergy, nuclear and hydropower technologies could, if not managed properly, have counteracting effects that compound existing water-related problems in a given locale (see McCollum et al for a summary and Davies et al. (2013); Byers et al. (2014); Fricko et al. (2016); Vidic et al. (2013); Miara et al. (2014); PBL (2012); Hanasaki et al. (2013); Hejazi et al. (2013); Fujimori et al. (2016)). On balance, the direct global energy sector water use and thermal water pollution of 1.5 °C and 2 °C mitigation pathways may result in trade-offs (Fricko et al, 2016, see also Figure 5.3). The estimates across different assessments vary however, significantly across scenarios, and adaptation in power plant cooling technology can considerably reduce freshwater withdrawals as well as thermal pollution. Global freshwater consumption increases across all of the investigated 2 °C scenarios as a result of rapidly expanding electricity demand in developing regions and the prevalence of freshwater-cooled thermal power generation. Reducing energy demand emerges as a robust strategy for water conservation, and enables increased technological flexibility on the supply side to fulfill ambitious climate objectives. The results underscore the importance of an integrated approach when developing water, energy, and climate policy, especially in regions where rapid growth in both energy and water demands is anticipated.

[*Note: Currently focused on energy-water implications. Need to add literature from other areas*]

5.5.1.5 Biodiversity

[Note: Results for biodiversity from comparable 1.5/2 °C pathways will be added later – the results are not available yet]

5.5.1.6 Other SD dimensions

[Note: further QUANTITATIVE results to be added here, in case they become available. It seems though that for other SD dimensions (not covered above), there are considerable knowledge gaps]

[INSERT FIGURE 5.3 HERE]

Figure 5.3: GHG emissions pathways and associated regional synergies and trade-offs for food security, air quality, and energy-related water consumption. Climate policy baseline pathways (No-Policy) are compared with INDC, 2 °C and 1.5 °C mitigation pathways. Sources: Fujimori et al, forthcoming (food security), Krey et al, forthcoming (Air pollution and water).

[*Note that the figure shows preliminary data, and will be extended for other sustainability dimensions, such as energy access and biodiversity. In addition, we'll add uncertainty ranges, global aggregated panels, and information on costs of how to resolve possible trade-offs through redistribution measures.]*

[*Note: we are planning a concluding paragraph here. Something like the paragraph below that would provide a concise overview of which emission reduction pathways with what particular mitigation mixes would most likely get us to the 1.5 °C target, with small and large overshoots. This may be repeating findings from Chapter 2, but it seems it would be helpful to have this picture laid out here with explicit reference to SD and what these pathways mean for CR development pathways.*

In other words, how would we unpack the 1.5 °C scenario line in the Figure 5.3? What is behind it? What emission reduction mixes would get us to the RCP1.9? Inevitably negative emissions? Inevitably nuclear? Any chances that we could just achieve it with renewables and lifestyle changes? We zoom in on those emerging pathways consistent with 1.5 °C and scrutinize them for their potential to enhance resilience and transformative change. But it would be good to have them stated here so we can see what].

In order to meet the 1.5 °C target, a full range of technological options, including large-scale deployment of Negative Emission Technologies (e.g. BECCS), will likely be required (Rogelj et al., 2015), particularly if downside risks associated with limited technology availability are to be avoided (Jakob and Steckel 2016b; Stechow et al. 2016). Consequently, the technological foundations for climate-resilient development pathways consistent with the 1.5 °C target are likely to entail full technological availability despite the evident risks and uncertainties associated with specific technological options (e.g. Smith et al., 2015). In contrast, options that improve energy efficiency may not allow us to meet the 1.5 °C target, even though they produce the least trade-offs with other energy-related SDGs (von Stechow et al. 2016).

5.5.2 Foundations for Climate-resilient Development Pathways

The feasibility of the 1.5 °C target and synergies with the SDGs rest upon certain prerequisite conditions being met. These prerequisite conditions can be considered 'foundations' to climate-resilient development pathways. They address the underlying social and governance/policy dimensions that need to be met in order to ensure that the emission pathways discussed above also fulfill the necessary equity and equality dimensions outlined in the 2030 Agenda. For instance, this includes considerations for the conditions that need to be in place so that poorer nations are enabled to design local solutions and afford externally produced technologies without succumbing to new dependencies or high risk pathways (UNRISD 2016).

This sub-section is divided into two parts: the first examines the literature regarding the social and governance/policy foundations for climate-resilient development pathways; the second describes concrete efforts of implementing such pathways on the ground, including good practices and encountered challenges.

[Note: *The text in the 2 sub-sections below shows possible entry points. We will add more specific literature]*

Understanding tensions between socio-technical pathways/transitions (Chapter 4) and resilient paths that 'leave no one behind' (2030 Agenda preamble) requires even closer attention to the social and policy/governance foundations for climate-resilient development pathways. The Shared Socio-economic Pathways (SSPs) provide a useful first insight into the social conditions that are required to meet stringent climate targets consistent with the 1.5 °C pathways (Box 5.2).

[START BOX 5.2 HERE]

Box 5.2: Shared Socio-economic Pathways (SSPs)

Out of the five SSPs, only SSP1 (Sustainability) and SSP2 (Middle of the Road) are consistent with RCP1.9 and hence envisioned as meeting stringent climate targets that secure a 1.5 °C pathway (Rogelj et al. in preparation) (Box 5.2 Figure 1a). SSP1 strongly emphasizes socially inclusive development, cross-sector and cross-level cooperation, poverty alleviation and inequality reduction, gender equality, and the prioritization of sustainability goals. A large emphasis is also placed upon education and healthcare provision. High-income countries are also assumed to de-emphasize economic growth as a policy goal, pursuing instead sustainable development goals, environmental awareness and less resource-intensive lifestyles (O'Neill et al. 2017). SSP2 stresses many of the same social conditions outlined in SSP1, though not to the same degree and not in a manner that deviates from historical patterns of development (business as usual). Moreover, mitigation requirements and costs are significantly higher than those modeled for SSP1 (Riahi et al. 2017).

The social foundations of these SSP scenarios differ significantly from SSP3 (Regional Rivalry) and SSP4 (Inequality) in which investments into human development cease altogether or continue in a highly unequal fashion, thus exacerbating pre-existing inequalities and differential socio-economic vulnerabilities. This would suggest that those social conditions that are premised upon inclusive and equal development are likely to underpin climate-resilient development pathways consistent with the 1.5 °C target and the SDGs. Nascent efforts to downscale the global SSP storylines to the sub-national level (e.g. Absar and Preston 2015) indicate the importance of factors (e.g. demographics and equity), actors (public and private institutions, civil society), and sectors (e.g. water, agriculture, and energy) for depicting nuanced social conditions.

[INSERT BOX 5.2 FIGURE 1 HERE]

Box 5.2, Figure 1: a) Roglej et al. (in preparation) – used in Chapter 2; b) Opportunity spaces and climate resilient pathways (IPCC 2014; Burkett et al. 2014)

[*Note: We imagine merging these two graphical ideas to illustrate the related to sustainability implications in each of the boxes and link them to possible climate-resilient development pathways*]

[END BOX 5.2 HERE]

5.5.2.1 Social Foundations

Recent literature suggests that climate-resilient development pathways that entail strong emphasis on transformative change toward sustainable development are likely to engender successful outcomes when the following conditions are met: adherence to universal and right-based policy approaches, integration of economic objectives into social and environmental norms, and genuine participatory decision making (UNRISD 2016). Solution-driven approaches require social, conceptual, institutional, policy, and technological innovations as well as close attention to evidence on the ground regarding the types of transformative change working in specific contexts and the various challenges and potential contradictions encountered along the way (ibid: 5). Such approaches are unlikely to succeed or be sustained without a core commitment to strong social policies, particularly those that 'expand rights, increase equality and reduce power asymmetries' (ibid: 10).

Another way of envisioning the social foundations that need to be met for climate-resilient development pathways is through the lens of what is known as 'a safe and just space for humanity' or short 'the doughnut' (Raworth 2012). This space emerges at the intersection of the planetary boundaries (Rockström et al. 2009) with social boundaries (sweet spot). The former has recently been updated to point to the importance of cross-scale interactions and the regional-level heterogeneity of the processes that underpin the boundaries notably in the case of climate change (Steffen et al. 2015). A proposed approach for sustainable development argues that the stable functioning of the Earth system is a prerequisite for thriving societies around the world, and that the planetary boundaries framework will need to be implemented alongside the achievement of targets aimed at more immediate human needs (Griggs et al. 2013). The latter (social foundations) draws attention to the critical human deprivations that need to be overcome. Figure 5.4 illustrates shortfalls below the eleven social foundations, with three not yet determined. Tackling inequalities is paramount in order to overcome these shortfalls, particularly resource inequalities in consumption and production (Raworth 2014).

[INSERT FIGURE 5.4 HERE]

Figure 5.4: A safe and just space for humanity: Shortfalls on social foundations (Raworth 2012) – [*to be updated in April 2017*]

Recent work draws attention to the social and climate policy arenas essential for generating transformative potential across the 17 SDGs (UNRISD 2016). Social policies together with care and social and solidarity economy are likely to be vital to overcome the shortfalls in several of the social foundations, remove entrenched inequalities, and enable and expedite climate-resilient-development pathways. Box 5.3 provides examples for innovative social policies as part of alternative development pathways. These examples indicate how to foster climate-resilient development in practice, through explicit emphasis on reducing multidimensional vulnerabilities and inequalities.

[START BOX 5.3 HERE]

Box 5.3: Alternative development pathways that foreground transformative social change

Development pathways that commit to social policies, particularly those that adopt social and solidarity economies, are well positioned to foster climate-resilient development. They emphasize inclusive and equitable development and, accordingly, attempt to reduce entrenched vulnerabilities and inequalities that drive risk to climatic hazards. Alternative pathways crafted predominantly by countries in the Global South include, for instance, the 'developmental welfare state' with emphasis on social policies (Draibe and Riesco

2007) and the 'Southern consensus' bringing together East Asian and Latin American models of social and economic development (Gore 2010). Social and solidarity economy (SSE) promotes cooperation, solidarity, democratic governance, collective action, active citizenship, and environmental stewardship (Bauhardt 2014; Wallimann 2014; Utting 2015). It understands ethics as a core ingredient of economic activity (Gibson-Graham 2008) and fosters economic and political empowerment (Agarwal 2015; Laville 2015; McMurtry 2013). As a counterforce to unsustainable development models, this form of economy can alter production and consumption patterns as well as social relations with disadvantaged members of society and, hence, is ideally positioned to implement the SDGs (UNTFSSE 2014; UNRISD 2016).

SEE is growing rapidly, encompassing alternative food networks, fair trade organizations, and broader social and environmental justice movements. Examples are the Zero Hunger (Hambre Cero) program for women groups and the Zero Usury micro-finance program in Nicaragua and the cooperative and labor solidarity movements in Costa Rica (Chamorro and Utting 2015), as well as self-help groups in India (Agarwal 2015) and community forest groups in Nepal. In high-income countries, SEE is the underlying principle for alternative food networks in Italy (Grasseni et al. 2013) and the Chantier Network in Quebec, Canada (Lewis and Conaty 2012). Other SEE models include la Via Campesina, Home Net, Street Net, the Global Alliance of Waste Pickers (UNRISD 2016). The concept of Buen Vivir, with origins in the worldview of Quechua peoples in the Andes, encapsulates the principles of a 'good life' based on de-growth, local trade systems, simplicity, solidarity, and food sovereignty. Despite critiques (e.g. Cochrane 2014; Calisto Friant and Langmore 2015), Buen Vivir and other SEE movements can shape policy debates to address climate change.
[END BOX 5.3 HERE]

5.5.2.2 Governance and Policy Foundations

Governance is a central consideration for climate-resilient development, particularly in the context of stringent climate targets and multiple, though not necessarily reinforcing, sustainable development objectives. This is because issues of power and politics indelibly shape development priorities. Politics, power, and interests are critical aspects of climate-motivated initiatives embedded in wider and more complex national policy contexts; they strongly influence the prospects of achieving integrated climate policy and development goals in practice (Naess et al. 2015; Sovacool et al. 2015), (Keohane and Victor 2016). Issues of power and political economy will play a key role in determining the potential for energy systems to meet climate, development, and adaptation needs simultaneously (Newell et al. 2014).

Growing literature indicates public participation is required for the coproduction of policy and to legitimize the complex trade off decisions and choices to achieve effective and equitable implementation of national goals for 1.5 °C (von Stechow et al. 2016)(Clark 2016) and enable disproportionate responses to emerge as preferences (Maor et al. 2017). Given the pivotal role of local governments in fostering sustainability transitions, these debates are most effective not only at the international or national level but also at the local level as they link climate change policies to local developmental priorities (Wamsler et al. 2014; Rescalvo et al. 2013). Integrated decision making at the municipal level and multi-level governance helps to identify both the challenges and benefits inherent in simultaneously pursuing multiple priorities (Shaw et al. 2014).

A key challenge lies in the cross-sectoral nature and complex interlinkages between the various sustainable development dimensions, and ways to capture these interlinkages through policy integration (Boas et al. 2016; Dimitrov 2016) (Rasul and Sharma 2016; Conway et al. 2015; Welsch et al. 2014) (Holden et al 2016). A body of literature on Climate Policy Integration has emerged in relation to the more established concept and practice of Environmental Policy Integration (Adelle and Russel 2013), to highlight that there is still lack of linkages between the governance of sustainable development, mitigation and adaptation (Casado-Asensio and Steurer 2017). The compatibility of climate policy integration with the overarching objective of sustainable development requires a set of conditions (Rietig 2013).

Indicators are useful to support processes of domestic debates and country-level decision making. They can assist policymakers and facilitate the shift from temperature targets to a plan for climate change rooted in a diversity of goals and targets, with the SDG indicators as a foundation (Briggs et al. 2015). Attention to sectoral granularity is important in order to track progress in transformations and their linkages to key development indicators (Peters et al. 2017). The AR4 noted, "growing use of indicators to manage and measure the sustainability of development at the macro and sectoral levels driven in part by the increasing emphasis on accountability in the context of governance and strategy initiatives. [*Note: need to see how past IPCC assessments have treated indicators in relation to climate governance concerns*]

Emerging literature on governance for climate resilience identifies the importance of dense linkages between local and national level planning through participatory processes that are inclusive, equitable, and accountable. There is agreement that such participatory processes legitimate government, and enable knowledge intensive decision making, through multiple fora that are flexible, innovative and responsive to changing conditions and complex, wicked problems (Termeer et al. 2016). The literature is divided about the tradeoffs between participation and speed in climate decision making (Irvin and Stansbury 2004; Lubell and Mewhirter 2016). However, transparent, inclusive governance processes are more likely to be regarded as equitable and legitimate as they reduce compliance costs and enhance the ease of implementation, even in the absence of consensus or where decisions are controversial (Maor et al. 2017; DeCaro et al. 2017).

5.5.3 Evidence of Successful Climate-resilient Development on the Ground

Climate-resilient development and grounded pathways toward transformative change also need to be seen from the perspective of evidence 'on the ground', including context-specific ingredients for success and challenges encountered. Choices that people make regarding particular decisions or pathways that are meaningful, socially desirable, and acceptable to them (including those that involves future generations) are likely to be embedded in normative values of justice, equity, and inclusion and inevitably will have to address uneven power dynamics and entrenched inequalities (UNRISD 2016).

Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways. Although transformations may be reactive, forced, or induced by random factors, they may also be deliberately created through social and political processes. Transformative social development entails changes in social structures, relations, and institutions, including gender, class, ethnicity and other dimensions of inequality and power struggles, as well as transitions to sustainable production and consumption (UNRISD 2016).

This sub-section reviews evidence on climate-resilient development, particularly at the level of communities - both communities of practice and place-specific communities. The case studies illustrate examples of what may be considered 'socially acceptable' transformation pathways - pathways that do not entail or exacerbate unacceptable risks, especially for already disadvantaged populations (von Stechow et al. 2016). Particular attention is paid to societal values, internal contestations, and the dynamics of such grounded efforts. Such nuances are not easily evaluated through scientifically and analytically rigorous analysis alone (Edenhofer and Minx 2014).

We provide an overview of enabling conditions and obstacles as well as concerns about the equity and ethical dimensions of transformation. This includes attention to policy conditions that could bring about sustainable transformative change (e.g. Burch et al. 2014); the geographical and spatial aspects of sustainability transitions (e.g. Coenen and Truffer 2012); and voices critical of the transformation pathways framing; e.g. political aspects of sustainable transitions (Shove and Walker 2007; Smith and Stirling 2010; Meadowcroft 2011; Patterson et al. 2015). Responses to critiques, (e.g. Geels 2011), and approaches that synthesize different perspectives, (e.g. O'Brien et al. 2013; Pelling et al. 2015), will also be discussed, incorporating insights from social-ecological systems framings.

5.5.3.1 Social learning

Social learning and adaptive management play a crucial role in transformative community-level processes addressing climate change within multiple-stressor approach (e.g. (Pollard et al. 2011; Butler et al. 2016) (Cundill et al. 2014). This entails attention to the role of social learning in shifting the balance of power in climate-resilient development processes (Fook et al. 2017). Case study experiences will illustrate the relevance of social learning for efforts to stay within the 1.5 °C target and beyond – e.g. given uncertainties in rate, timing and scale of impacts, and potential consequences of higher rates of warming (e.g. Fook 2015).

5.5.3.2 Equity, right, and justice

There is growing evidence on the importance of focusing on and supporting the procedural and dynamic elements in community-level transformative processes, such as procedural justice, human agency, and rights, the latter including rights to development. Assessing how these approaches are employed helps to address systemic causes of vulnerability and disempowerment. [*Note: see Tanner et al. (2014) on the need to consider "adaptive livelihood systems in the context of wider transformational changes", and on how integrating a livelihood perspective into resilience thinking emphasizes equity and rights considerations; and* MacKinnon and Derickson (2013) *on resourcefulness and agency*]

5.5.3.3 Indicators

Indicators and processes are crucial for tracking progress towards climate resilience and sustainable development on the ground. This includes context-specific and locally developed criteria for assessing climate-resilient livelihoods (e.g. IFAD's Adaptation for Smallholder Agriculture Programme). There is emerging evidence on socially salient tipping points in the context of adaptation pathways (Barnett et al. 2014; Gorddard et al. 2016; Kwadijk et al. 2010), as well as the role of learning-by-doing, experimentation, and empowered agency, with parallels to be explored for climate-resilient development pathways.

[START BOX 5.4 HERE]

Box 5.4: Case studies: Bolsa Verde, Transitions Towns, Urban Innovations, Indigenous communities in the Arctic, and others…

This box provides short examples of climate-resilient development from countries at different stages of development. These case studies highlight ingredients for success but also address difficulties and dilemmas. They cast light on particular characteristics of climate-resilient development in specific contexts and explore some key differences between good climate risk-management and climate-resilient development.

Bolsa Verde, established in Brazil in 2011, combines a Payment for Ecosystem Services (PES) Program (*Bolsa Floresta*) with a social protection program (*Bolsa Familia*) with its main aim to reduce extreme poverty in rural areas and conserve ecosystems. By the end of 2015, >70,000 households received 300 reais/month (~$US125) and environmental training to engage in sustainable forest use practices (Cook et al. 2012; Coudel et al. 2015; OECD 2015)(ILO 2016). Similar pro-poor PES programs exist, inter alia, in Costa Rica, Mexico, Ecuador, China, and South Africa with focus areas on avoiding deforestation and severe flooding from social erosion (ILO 2016). Yet, caution is required that PES schemes don't trade social outcomes for market-based business models that risk perpetuating inequality and injustice (e.g. Fairhead et al. 2012; Muradian et al. 2013; Hahn et al. 2015).

Transition Towns: The Transition Town is an international movement that originated in Totnes, UK, in 2006 and has now spread to over 1,300 initiatives in over 50 countries. It is based on community projects that adopt low-carbon economies, food self-sufficiency, energy efficiency, and recycling to foster community resilience. Such 'progressive localism' provides concrete opportunities to prepare for peak-oil yet also triggers ethical dilemmas of care (e.g. (Cretney et al. 2016; Mason and Whitehead 2012; Feola and Nunes 2014; Mehmood 2016).

Pacific Islands: "Yumi stap redi long climate change" program– The Vanuatu NGO Climate Change Adaptation Program was founded in Vanuatu in 2012 to increase the resilience of Vanuatu communities to the impacts of climate change while recognizing that adaptive capacity is severely limited (Sovacool et al. 2017). The focus has been on equitable governance (with particular attention to supporting women's agency in decision making through allied programs addressing domestic violence and participation) together with rights-based education focused on the structural constraints on adaptive capacity that exacerbate social marginalization and exclusion; institutional reforms for greater transparency and accountability (Ensor 2016; Davies 2015); and participatory education for climate smart agricultural (Ensor 2016; Sterett 2015). By

2014, 5,400 women, men and young people in 30 communities in the provinces of Torba, Tafea, Shefa and Penama had participated in rights-based community wellbeing and climate awareness education (United Nations 2016). Related climate-resilient community frameworks have been established in Papua New Guinea, Timor Leste, Vanuatu and Vietnam (Sterett 2015). The role of external non-governmental agencies is proposed to be limited to providing access to information so communities are empowered to address structural and agency constraints and local technical and decision making capacity is enhanced (Ensor 2016).

Urban innovation and governance: how cities implement climate resilience in socially salient ways.

Indigenous populations (e.g. in the Arctic) and use of traditional knowledge to embrace change, continuity, and transformation in socially and culturally salient climate-resilient development.

Vikalp Sangam (Alternatives Confluence) in India: leading to Alternative Transformations Framework that aims to gain more in-depth understanding of alternative transformations in political, economic, social, cultural and ecological fronts, and of the worldviews that underlie or inform such transformations.

Caribbean risk management of extreme events

Other examples:

- Book: Carrapatoso, Astrid, and Edith Kürzinger. *Climate-Resilient Development: Participatory Solutions from Developing Countries*. Routledge, 2013
- some policy-level case studies

[END BOX 5.4 HERE]

5.6 Synthesis and Research Gaps

This is the concluding section of the chapter. It will provide a synthesis of the sections of this chapter and tie the findings back to preceding chapters of the report, to close the arc of the storyline that Chapter 1 initiated. The section will close with discussing particular research gaps.

References

Absar, S. M., and B. L. Preston, 2015: Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. *Glob. Environ. Chang.*, **33**, 83–96, doi:10.1016/j.gloenvcha.2015.04.004. http://dx.doi.org/10.1016/j.gloenvcha.2015.04.004.

Adelle, C., and D. Russel, 2013: Climate Policy Integration: A Case of Déjà Vu? *Environ. Policy Gov.*, **23**, 1–12, doi:10.1002/eet.1601.

Agarwal, B., 2015: The power of numbers in gender dynamics: illustrations from community forestry groups. *J. Peasant Stud.*, **42**, 1–20, doi:10.1080/03066150.2014.936007. http://dx.doi.org/10.1080/03066150.2014.936007.

Aha, B., and J. Z. Ayitey, 2017: Biofuels and the hazards of land grabbing: Tenure (in)security and indigenous farmers' investment decisions in Ghana. *Land use policy*, **60**, 48–59, doi:10.1016/j.landusepol.2016.10.012. http://dx.doi.org/10.1016/j.landusepol.2016.10.012.

Ahmed, S. A., N. S. Diffenbaugh, and T. W. Hertel, 2009: Climate volatility deepens poverty vulnerability in developing countries. *Environ. Res. Lett.*, **4**, 34004, doi:10.1088/1748-9326/4/3/034004. http://web.ics.purdue.edu/~hertel/data/uploads/publications/erl-ahmed-diffenbaugh-hertel.pdf%5Cnhttp://stacks.iop.org/1748-9326/4/i=3/a=034004?key=crossref.8a7ab4b622d0b9753cf1eecc77074f32.

Aitsi-Selmi, A., S. Egawa, H. Sasaki, C. Wannous, and V. Murray, 2015: The Sendai Framework for Disaster Risk Reduction: Renewing the Global Commitment to People's Resilience, Health, and Well-being. *Int. J. Disaster Risk Sci.*, **6**, 164–176, doi:10.1007/s13753-015-0050-9.

Akimoto, K., F. Sano, and B. S. Tehrani, 2016: The analyses on the economic costs for achieving the nationally determined contributions and the expected global emission pathways. *Evol. Institutional Econ. Rev.*, 1–14, doi:10.1007/s40844-016-0049-y. http://link.springer.com/10.1007/s40844-016-0049-y.

Alderman, H., J. Hoddinott, and B. Kinsey, 2006: Long term consequences of early childhood malnutrition. *Oxf. Econ. Pap.*, **58**, 450–474, doi:10.1093/oep/gpl008.

Alkire, S., 2008: *Choosing Dimensions: The Capability Approach and Multidimensional Poverty Choosing Dimensions: the Capability Approach and Multidimensional Poverty*. 28 pp. http://mpra.ub.uni-muenchen.de/8862/.

Alkire, S., and J. E. Foster, 2013: *Measuring Acute Poverty in the Developing World: Robustness and Scope of the Multidimensional Poverty Index*.

Alston, M., 2014: Gender mainstreaming and climate change. *Womens. Stud. Int. Forum*, **47**, 287–294, doi:10.1016/j.wsif.2013.01.016. http://dx.doi.org/10.1016/j.wsif.2013.01.016.

Alston, M., and K. Whittenbury, 2013: Research, action and policy: Addressing the gendered impacts of climate change. *Res. Action Policy Addressing Gendered Impacts Clim. Chang.*, 1–281, doi:10.1007/978-94-007-5518-5.

Althor, G., J. E. M. Watson, and R. A. Fuller, 2016: Global mismatch between greenhouse gas emissions and the burden of climate change. *Sci. Rep.*, **6**, 20281, doi:10.1038/srep20281. http://www.nature.com/articles/srep20281.

Altieri, K. E., H. Trollip, T. Caetano, A. Hughes, B. Merven, and H. Winkler, 2016: Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Clim. Policy*, 1–14, doi:10.1080/14693062.2016.1150250.

Amin, S., 2006: The millennium development goals: A critique from the South. *Mon. Rev.*, **57**, 1–15. http://monthlyreview.org/2006/03/01/the-millennium-development-goals-a-critique-from-the-south.

Anderson, K., and G. Peters, 2016: The trouble with negative emissions. *Science (80-.).*, **354**, 182–183, doi:10.1126/science.aah4567. http://science.sciencemag.org/content/354/6309/182.

Anderson, R. E., 2017: Well-Being, Future Generations, and Prevention of Suffering from Climate Change. *Alleviating World Suffering, Social Indicators Research*, R.E Anderson, Ed., Springer International Publishing, 431–447.

Ansuategi, A., P. Greno, V. Houlden, A. Markandya, L. Onofri, H. Picot, G.-M. Tsarouchi, and N. Walmsley, 2015: *The impact of climate change on the achievement of the post-2015 sustainable development goals*. 1-84 pp.

Asseng, S., and Coauthors, 2015: Rising temperatures reduce global wheat production. *Nat. Clim. Chang.*, **5**, 143–147, doi:10.1038/nclimate2470.

Ault, T. R., J. E. Cole, J. T. Overpeck, G. T. Pederson, and D. M. Meko, 2014: Assessing the risk of persistent drought using climate model simulations and paleoclimate data. *J. Clim.*, **27**, 7529–7549, doi:10.1175/JCLI-D-12-00282.1.

Ayers, J. M., S. Huq, H. Wright, A. M. Faisal, and S. T. Hussain, 2014: Mainstreaming climate change adaptation into development in Bangladesh. *Clim. Dev.*, **6**, 293–305, doi:10.1002/wcc.226. http://dx.doi.org/10.1080/17565529.2014.977761.

Bahu, J.-M., A. Koch, E. Kremers, and S. M. Murshed, 2013: Towards a 3d Spatial Urban Energy Modelling Approach. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, **II-2/W1**, 33–41, doi:10.5194/isprsannals-II-2-W1-33-2013. http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/II-2-W1/33/2013/isprsannals-II-2-W1-33-2013.pdf.

Baker, A. C., P. W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.*, **80**, 435–471, doi:10.1016/j.ecss.2008.09.003. http://dx.doi.org/10.1016/j.ecss.2008.09.003.

Bank, W., 2010: *Cities and Climate Change : An Urgent Agenda. Knowledge papers no. 10.* Wahington D.C., 81 pp. http://hdl.handle.net/10986/17381.

Barbier, E. B., 2014: Climate change mitigation policies and poverty. *Wiley Interdiscip. Rev. Clim. Chang.*, **5**, 483–491, doi:10.1002/wcc.281.

Barnett, J., S. Graham, C. Mortreux, R. Fincher, E. Waters, and A. Hurlimann, 2014: A local coastal adaptation pathway. *Nat. Clim. Chang.*, **4**, 1103–1108, doi:10.1038/nclimate2383. http://www.nature.com/doifinder/10.1038/nclimate2383.

Bassu, S., N. Brisson, J. Durand, K. Boote, and J. Lizaso, 2014: How do various maize crop models vary in their responses to climate change factors ? *Glob. Chang. Biol.*, **20**, 2301–2320, doi:10.1111/gcb.12520.

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, J. Williams, and F. Jotzo, 2016: The need for national deep decarbonization pathways for effective climate policy. *Clim. Policy*, **16**, 7–26, doi:10.1080/14693062.2016.1173005. http://dx.doi.org/10.1080/14693062.2016.1173005 (Accessed March 23, 2017).

Bauhardt, C., 2014: Solutions to the crisis? The Green New Deal, degrowth, and the solidarity economy: Alternatives to the capitalist growth economy from an ecofeminist economics perspective. *Ecol. Econ.*, **102**, 60–68.

Beckerman, 1995: How would you like your “sustainability”, Sir? weak or strong? a reply to my critics. *Environ. Values*, **4**, 167–179, doi:10.3197/096327195776679574. http://eprints.ucl.ac.uk/17882/.

Beg, N., and Coauthors, 2002: Linkages between climate change and sustainable development. *Clim. Policy*, **2**, 129–144, doi:10.1016/S1469-3062(02)00028-1.

Bendlin, L., 2014: Women’s human rights in a changing climate: highlighting the distributive effects of climate policies. *Cambridge Rev. Int. Aff.*, **27**, 680–698, doi:10.1080/09557571.2014.960507.

Berbes-Blazquez, M., C. L. Mitchell, S. L. Burch, and J. Wandel, 2017: Understanding climate change and resilience: assessing strengths and opportunities for adaptation in the Global South. *Clim. Change*, **141**, 227–241, doi:10.1007/s10584-017-1897-0.

Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac, and J. Eom, 2015: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change*, **90**, 62–72, doi:10.1016/j.techfore.2013.10.001. http://dx.doi.org/10.1016/j.techfore.2013.10.001.

Bhattarai, B., R. Beilin, and R. Ford, 2015: Gender, Agrobiodiversity, and Climate Change: A Study of Adaptation Practices in the Nepal Himalayas. *World Dev.*, **70**, 122–132, doi:10.1016/j.worlddev.2015.01.003. http://dx.doi.org/10.1016/j.worlddev.2015.01.003.

Birk, T., 2014: Assessing vulnerability to climate change and socioeconomic stressors in the Reef Islands group, Solomon Islands. *Geogr. Tidsskr.*, **114**, 59–75, doi:10.1080/00167223.2013.878228.

Blicharska, M., and Coauthors, 2017: Steps to overcome the North-South divide in research relevant to climate change policy and practice. *Nat. Clim. Chang.*, **7**, doi:10.1038/nclimate3163.

Boas, I., F. Biermann, and N. Kanie, 2016: Cross-sectoral strategies in global sustainability governance: towards a nexus approach. *Int. Environ. Agreements Polit. Law Econ.*, **16**, 449–464, doi:10.1007/s10784-016-9321-1.

Boer, R., and Coauthors, 2016: *Pathways to deep decarbonizing agriculture, forest and other land uses sector in indonesia*. 52 pp.

Boucher, O., and Coauthors, 2016: Opinion: In the wake of Paris Agreement, scientists must embrace new directions for climate change research. *Proc. Natl. Acad. Sci.*, **113**, 7287–7290, doi:10.1073/pnas.1607739113. http://www.pnas.org/lookup/doi/10.1073/pnas.1607739113.

Briggs, S., C. F. Kennel, and D. G. Victor, 2015: Planetary vital signs. *Nat. Clim. Chang.*, **5**, 969–970, doi:10.1038/nclimate2828. http://dx.doi.org/10.1038/nclimate2828%5Cn10.1038/nclimate2828.

Brown, H. C. P., 2011: Gender, climate change and REDD+ in the Congo Basin forests of Central Africa. *Int. For. Rev.*, **13**, 163–176, doi:10.1505/146554811797406651.

Buck, H. J., A. R. Gammon, and C. J. Preston, 2014: Gender and geoengineering. *Hypatia*, **29**, 651–669, doi:10.1111/hypa.12083.

Burch, S., A. Shaw, A. Dale, and J. Robinson, 2014: Triggering transformative change: a development path approach to climate change response in communities. *Clim. Policy*, **14**, 467–487, doi:10.1080/14693062.2014.876342. http://www.tandfonline.com/doi/abs/10.1080/14693062.2014.876342.

Burkett, V. R., A. G. Suarez, M. Bindi, C. Conde, R. Mukerji, M. J. Prather, A. L. S. Clair, and G. W. Yohe, Point of departure. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 169–194.

Butler, J. R. A., and Coauthors, 2016: Scenario planning to leap-frog the Sustainable Development Goals: An adaptation pathways approach. *Clim. Risk Manag.*, **12**, 83–99, doi:10.1016/j.crm.2015.11.003. http://dx.doi.org/10.1016/j.crm.2015.11.003.

Cai, Y., T. M. Lenton, and T. S. Lontzek, 2016: Risk of multiple interacting tipping points should encourage rapid CO2

emission reduction. *Nat. Clim. Chang.*, **6**, 520–525, doi:10.1038/nclimate2964. http://www.nature.com/doifinder/10.1038/nclimate2964.
Calisto Friant, M., and J. Langmore, 2015: The buen vivir: a policy to survive the Anthropocene? *Glob. Policy*, **6**, 64–71.
Carr, E. R., and M. C. Thompson, 2014: Gender and Climate Change Adaptation in Agrarian Settings. *Geogr. Compass*, **8/3**, 182–197, doi:10.1111/gec3.12121.
Casado-Asensio, J., and R. Steurer, 2017: Integrated strategies on sustainable development, climate change mitigation and adaptation in Western Europe: communication rather than coordination. *J. Public Policy*, **343**, 437–473, doi:10.1017/S0143814X13000287. https://www.cambridge.org/core/services/aop-cambridge-core/content/view/S0143814X13000287 (Accessed March 24, 2017).
Cash, D. W., N. W. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young, 2006: Cross-Scale Dynamics: Governance and Information in a Multilevel World. *Ecol. Soc.*, **11**, 8–19, doi:8. http://www.ecologyandsociety.org/vol11/iss2/art8/.
Casillas, C. E., and D. M. Kammen, 2012: Quantifying the social equity of carbon mitigation strategies. *Clim. Policy*, **12**, 690–703, doi:10.1080/14693062.2012.669097.
Challinor, A. J., J. Watson, D. B. Lobell, S. M. Howden, D. R. Smith, and N. Chhetri, 2014: A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Chang.*, **4**, 287–291, doi:10.1038/nclimate2153.
Chamorro, A., and P. Utting, 2015: *Políticas Públicas y la Economía Social y Solidaria: Hacia un Entorno Favorable. El Caso de Nicaragua*. ILO/ILO-ITC, Geneva/Turin,.
Chang, R., J. Zuo, Z. Zhao, V. Soebarto, G. Zillante, and X. Gan, 2017: Approaches for Transitions Towards Sustainable Development: Status Quo and Challenges. *Sustain. Dev.*, doi:10.1002/sd.1661. http://doi.wiley.com/10.1002/sd.1661 (Accessed April 13, 2017).
Chen, C., C. Qian, A. Deng, and W. Zhang, 2012: Progressive and active adaptations of cropping system to climate change in Northeast China. *Eur. J. Agron.*, **38**, 94–103, doi:10.1016/j.eja.2011.07.003. http://dx.doi.org/10.1016/j.eja.2011.07.003.
Chen, P. Y., C. C. Chen, L. Chu, and B. McCarl, 2015: Evaluating the economic damage of climate change on global coral reefs. *Glob. Environ. Chang.*, **30**, 12–20, doi:10.1016/j.gloenvcha.2014.10.011. http://dx.doi.org/10.1016/j.gloenvcha.2014.10.011.
Cheung, W. W. L., and G. Reygondeau, 2016: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science (80-.).*, **354**, 1591–1594, doi:10.1126/science.aag2331. http://science.sciencemag.org/content/354/6319/1591?rss=1.
Cinner, J. E., and Coauthors, 2016: A framework for understanding climate change impacts on coral reef social-ecological systems. *Reg. Environ. Chang.*, **16**, 1133–1146, doi:10.1007/s10113-015-0832-z.
Clark, P. U., and Coauthors, 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nat. Clim. Chang.*, **6**, 360–369, doi:10.1038/nclimate2923. http://www.nature.com/doifinder/10.1038/nclimate2923.
Clark, W. C., L. Van Kerkhoff, L. Lebel, and G. C. Gallopin, 2016: Crafting usable knowledge for sustainable development. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, doi:10.1073/pnas.1601266113.
Clarke, L. E., and Coauthors, 2014: Assessing transformation pathways. *Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 413–510. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Assessing+Transformation+Pathways#4.
Clemens, M. A., C. J. Kenny, and T. J. Moss, 2007: The Trouble with the MDGs: Confronting Expectations of Aid and Development Success. *World Dev.*, **35**, 735–751, doi:10.1016/j.worlddev.2006.08.003.
Cochrane, R., 2014: Climate change, buen vivir, and the dialectic of enlightenment: Toward a feminist critical philosophy of climate justice. *Hypatia*, **29**, 576–598.
Coenen, L., and B. Truffer, 2012: Places and Spaces of Sustainability Transitions: Geographical Contributions to an Emerging Research and Policy Field. *Eur. Plan. Stud.*, **20**, 367–374, doi:10.1080/09654313.2012.651802.
Colenbrander, S., and Coauthors, 2016: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environ. Urban.*, 1–20, doi:10.1177/0956247816677775.
Conway, D., and Coauthors, 2015: Climate and southern Africa's water-energy-food nexus. *Nat. Clim. Chang.*, **5**, 837–846, doi:10.1038/Nclimate2735.
Cook, S., K. Smith, and P. Utting, 2012: *Green economy or green society? Contestation and policies for a fair transition*. UNRISD Occasional Paper: Social Dimensions of Green Economy and Sustainable Development,.
Coopman, A., D. Osborn, F. Ullah, E. Auckland, and G. Long, 2016: *Seeing the whole: Implementing the SDGs in an Integrated and Coherent Way*. 36 pp.
Coudel, E., and Coauthors, 2015: The rise of PES in Brazil: from pilot projects to public policies. *Handbook of Ecological Economics*, J. Martinez-Alier and R. Muradian, Eds., Edward Elgar Publishing, Cheltenham, UK, p. 450.
Coumou, D., and A. Robinson, 2013: Historic and future increase in the global land area affected by monthly heat extremes. *Environ. Res. Lett.*, **8**, 34018, doi:10.1088/1748-9326/8/3/034018. http://stacks.iop.org/1748-

9326/8/i=3/a=034018?key=crossref.8f6f762083fe1e1708ea64b00d47ed7b.
Cramer, W., G. W. Yohe, M. Auffhammer, C. Huggel, and U. Molau, 2014: Detection and Attribution of Observed Impacts. *IPCC, AR5, WGII*, 979–1037.
Cretney, R. M., A. C. Thomas, and S. Bond, 2016: Maintaining grassroots activism: Transition Towns in Aotearoa New Zealand. *N. Z. Geog.*, **72**, 81–91.
Creutzig, F., and Coauthors, 2016: Urban infrastructure choices structure climate solutions. *Nat. Clim. Chang.*, **6**, 1054, doi:10.1038/nclimate3169. http://dx.doi.org/10.1038/nclimate3169.
Creutzig, F., and Coauthors, 2015: Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, **7**, 916–944, doi:10.1111/gcbb.12205.
Damm, A., J. Köberl, F. Prettenthaler, N. Rogler, and C. Töglhofer, 2016: Impacts of +2°C global warming on electricity demand in Europe. *Clim. Serv.*, 1–19, doi:10.1016/j.cliser.2016.07.001.
Dasgupta, P., 2016: *Climate Sensitive Adaptation in Health: Imperatives for India in a Developing Economy Context*. Springer,.
Davies, K., Kastom, Climate Change and Intergenerational Democracy: Experiences from Vanuatu.
De Cian, E., A. F. Hof, G. Marangoni, M. Tavoni, and D. P. van Vuuren, 2016: Alleviating inequality in climate policy costs: an integrated perspective on mitigation, damage and adaptation. *Environ. Res. Lett.*, **11**, 74015, doi:10.1088/1748-9326/11/7/074015.
Death, C., and C. Gabay, 2015: Doing Biopolitics Differently? Radical Potential in the Post-2015 MDG and SDG Debates. *Globalizations*, **12**, 597–612, doi:10.1080/14747731.2015.1033172. 10.1080/14747731.2015.1033172%5Cnhttp://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=103225048&lang=pt-br&site=ehost-live (Accessed March 22, 2017).
DeCaro, D. A., C. Anthony, T. Arnold, E. F. Boamah, and A. S. Garmestani, 2017: Understanding and applying principles of social cognition and decision making in adaptive environmental governance. *Ecol. Soc.*, **22**, 33, doi:doi.org/10.5751/ES-09154-220133. https://doi.org/10.5751/ ES-09154-220133.
DeClerck, F., and Coauthors, 2016: Agricultural ecosystems and their services: the vanguard of sustainability? *Curr. Opin. Environ. Sustain.*, **23**, 92–99, doi:10.1016/j.cosust.2016.11.016. http://dx.doi.org/10.1016/j.cosust.2016.11.016.
Dell, M., B. F. Jones, and B. A. Olken, 2009: Temperature and income: reconciling new cross-sectional and panel estimates. *Am. Econ. Rev.*, **99**, 198–204, doi:10.3386/w14680.
Denton, F., and Coauthors, 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1101–1131.
Dercon, S., and C. Porter, 2014: Live aid revisited: Long-term impacts of the 1984 Ethiopian famine on children. *J. Eur. Econ. Assoc.*, **12**, 927–948, doi:10.1111/jeea.12088.
Diffenbaugh, N. S., D. L. Swain, and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proc. Natl. Acad. Sci.*, **112**, 3931–3936, doi:10.1073/pnas.1422385112.
Dimitrov, R. S., 2016: The Paris agreement on climate change: Behind closed doors. *Glob. Environ. Polit.*, **16**, doi:10.1162/GLEP_a_00361.
Dong, W., J. Chen, B. Zhang, Y. Tian, and W. Zhang, 2011: Responses of biomass growth and grain yield of midseason rice to the anticipated warming with FATI facility in East China. *F. Crop. Res.*, **123**, 259–265, doi:10.1016/j.fcr.2011.05.024. http://dx.doi.org/10.1016/j.fcr.2011.05.024.
Draibe, S. M., and M. Riesco, 2007: Latin America: a new developmental welfare state in the making? *IPSA - 21st World Congress of Political Science*, New York, Palgrave Macmillan.
Dunne, J. P., R. J. Stouffer, and J. G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nat. Clim. Chang.*, **3**, 563–566, doi:10.1038/nclimate1827.
Edenhofer, O., and J. Minx, 2014: Mapmakers and navigators, facts and values. *Science (80-.).*, **345**, 37–38.
Editors, 2015: The 169 Commandments. *The Economist*.
Ensor, J., 2016: *Adapation and Resilience in Vanuatu: Interpreting community perceptions of vulnerability, knowledge and power for community-based adaptation programming.* Stockholm, 31 pp. https://www.sei-international.org/mediamanager/documents/Publications/Climate/Oxfam-SEI-2016-Vanuatu-adaptation-resilience.pdf.
Eom, J., J. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and P. Van Vururen, Detlef, 2015: The impact of near-term climate policy choices on technology and emission transition pathways. *Technol. Forecast. Soc. Change*, **90**, 73–88.
Escobar, A., 1994: *Encountering Development: The making and unmaking of the third world*. Princeton University Press,.
Etienne, M., D. R. du Toit, and S. Pollard, 2011: ARDI: A co-construction method for participatory modeling in natural resources management. *Ecol. Soc.*, **16**.

Fairhead, J., M. Leach, and I. Scoones, 2012: Green Grabbing: a new appropriation of nature? *J. Peasant Stud.*, **39**, 237–261.

Fehling, M., B. D. Nelson, and S. Venkatapuram, 2013: Limitations of the Millennium Development Goals: a literature review. *Glob. Public Health*, **8**, 1109–1122, doi:10.1080/17441692.2013.845676. http://www.tandfonline.com/doi/full/10.1080/17441692.2013.845676 (Accessed March 22, 2017).

Feola, G., and R. Nunes, 2014: Success and failure of grassroots innovations for addressing climate change: The case of the Transition Movement. *Glob. Environ. Chang.*, **24**, 232–250.

Fischer, E. M., and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Chang.*, **5**, 560–564, doi:10.1038/nclimate2617. http://www.nature.com/doifinder/10.1038/nclimate2617.

Fleurbaey, M., 2009: Beyond GDP: The Quest for a Measure of Social Welfare. *J. Econ. Lit.*, **47**, 1029–1075, doi:10.1257/jel.47.4.1029. http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=46814557&site=ehost-live%5Cnhttp://www.jstor.org/stable/pdf/40651532.pdf?acceptTC=true.

Fleurbaey, M., and D. Blanchet, 2013: *Beyond GDP: Measuring welfare and assessing sustainability*. Oxford University Press,.

Fleurbaey, M., and Coauthors, 2014: Sustainable Development and Equity. *Clim. Chang. 2014 Mitig. Clim. Chang.*, 283–350. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.

Folke, C., 2006: Resilience: The emergence of a perspective for social--ecological systems analyses. *Glob. Environ. Chang.*, **16**, 253–267, doi:http://dx.doi.org/10.1016/j.gloenvcha.2006.04.002.

Fook, T. C. T., 2015: Transformational processes for community-focused adaptation and social change: a synthesis. *Clim. Dev.*, **5529**, 1–17, doi:10.1080/17565529.2015.1086294. http://www.tandfonline.com/doi/full/10.1080/17565529.2015.1086294.

Fricko, O., S. C. Parkinson, N. Johnson, M. Strubegger, T. H. M. Van Vliet, and K. Riahi, 2016: Energy sector water use implications of a 2 degree climate policy. *Environ. Res. Lett.*, **11**, 34011, doi:10.1088/1748-9326/11/3/034011. http://dx.doi.org/10.1088/1748-9326/11/3/034011.

Fukuda-Parr, S., 2016: From the Millennium Development Goals to the Sustainable Development Goals: shifts in purpose, concept, and politics of global goal setting for development. *Gend. Dev.*, **24**, 43–52, doi:10.1080/13552074.2016.1145895. http://www.tandfonline.com/doi/full/10.1080/13552074.2016.1145895 (Accessed March 22, 2017).

Funfgeld, H., and D. McEvoy, 2011: Framing Climate Change Adaptation in Policy and Practice. http://www.vcccar.org.au/files/vcccar/Framing_project_workingpaper1_190411.pdf.

Fuss, S., and Coauthors, 2014: Betting on negative emissions. *Nat. Clim. Chang.*, **4**, 850–853, doi:10.1038/nclimate2392. http://dx.doi.org/10.1038/nclimate2392%5Cn10.1038/nclimate2392.

Gallup, J. L., and J. D. Sachs, 2001: The economic burden of malaria. *Am. J. Trop. Med. Hyg.*, **64**.

Gattuso, J.-P., and Coauthors, 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science (80-.).*, **349**, aac4722-aac4722, doi:10.1126/science.aac4722. http://www.sciencemag.org/cgi/doi/10.1126/science.aac4722 (Accessed March 24, 2017).

Geels, F. W., 2011: The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environ. Innov. Soc. Transitions*, **1**, 24–40, doi:10.1016/j.eist.2011.02.002. http://dx.doi.org/10.1016/j.eist.2011.02.002.

Gibson-Graham, J. K., 2008: Diverse economies: performative practices forother worlds'. *Prog. Hum. Geogr.*, **32**, 613–632.

Giwa, A., A. Alabi, A. Yusuf, and T. Olukan, 2017: A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. *Renew. Sustain. Energy Rev.*, **69**, doi:10.1016/j.rser.2016.11.160.

Gorddard, R., M. J. Colloff, R. M. Wise, D. Ware, and M. Dunlop, 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environ. Sci. Policy*, **57**, 60–69, doi:10.1016/j.envsci.2015.12.004. http://dx.doi.org/10.1016/j.envsci.2015.12.004.

Gore, C., 2010: The MDG paradigm, productive capacities and the future of poverty reduction. *IDS Bull.*, **41**, 70–79.

Gosh, D., F. Sengers, A. J. Wieczorek, B. Gosh, J. Roy, and R. Raven, 2016: Urban Mobility Experiments in India and Thailand, in The Experimental City. *The Experimental City*, J. Evans, A. Karvonen, and R. Raven, Eds., Routledge.

Gosling, S. N., and N. W. Arnell, 2016: A global assessment of the impact of climate change on water scarcity. *Clim. Change*, **134**, 371–385, doi:10.1007/s10584-013-0853-x.

Gough, I., 2011: *Climate change, double injustice and social policy: a case study of the United Kingdom*. Geneva,.

Granoff, I., and Coauthors, 2015: *Zero poverty, zero emissions: Eradicating extreme poverty in the climate crisis*. London, 1-56 pp.

Grasseni, C., F. Forno, and S. Signori, 2013: *Beyond alternative food networks: Italy's Solidarity Purchase Groups*. UNRISD, London, UK,.

Green, D., 2016: The spatial distribution of extreme climate events, another inequity for the world's most vulnerable people. *Environ. Res. Lett.*, **11**, 1–2, doi:10.1088/1748-9326/11/9/091002. http://dx.doi.org/10.1088/1748-

9326/11/9/091002.

Griggs, D., M. Stafford Smith, J. Rockstrom, Marcus Ohman, O. Gaffney, G. Glaser, N.Kanie, W.Steffen, and P. S., 2014: An integrated framework for sustainable development goals. *Ecol. Soc.*, **19**, 49.

Griggs, D., and Coauthors, 2013: Policy: Sustainable development goals for people and planet. *Nature*, **495**, 305–307, doi:10.1038/495305a. http://www.ncbi.nlm.nih.gov/pubmed/23518546.

Griggs, D., and Coauthors, 2013: Policy : Sustainable development goals for people and planet. *Nature*, **495**, 305–307, doi:10.1038/495305a.

Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Chang.*, **23**, 485–498, doi:10.1016/j.gloenvcha.2012.12.006.

Hahn, T., C. McDermott, C. Ituarte-Lima, M. Schultz, T. Green, and M. Tuvendal, 2015: Purposes and degrees of commodification: Economic instruments for biodiversity and ecosystem services need not rely on markets or monetary valuation. *Ecosyst. Serv.*, **16**, 74–82.

Hajer, M., and Coauthors, 2015: Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustain.*, **7**, doi:10.3390/su7021651.

Hák, T., S. Janoušková, and B. Moldan, 2016: Sustainable Development Goals: A need for relevant indicators. *Ecol. Indic.*, **60**, 565–573, doi:10.1016/j.ecolind.2015.08.003.

Hallegatte, S., and Coauthors, 2016: *Shock Waves: Managing the Impacts of Climate Change on Poverty*.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nat. Clim. Chang.*, **3**, 802–806.

Hallegatte, S., and Coauthors, 2016: Mapping the climate change challenge. *Nat. Clim. Chang.*, **6**, 663–668, doi:10.1038/nclimate3057. http://dx.doi.org/10.1038/nclimate3057%5Cnhttp://www.nature.com/doifinder/10.1038/nclimate3057.

Hansen, G., D. Stone, M. Auffhammer, C. Huggel, and W. Cramer, 2016: Linking local impacts to changes in climate: a guide to attribution. *Reg. Environ. Chang.*, **16**, 527–541, doi:10.1007/s10113-015-0760-y.

Harrington, L. J., D. J. Frame, E. M. Fischer, E. Hawkins, M. Joshi, and C. D. Jones, 2016: Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environ. Res. Lett.*, **11**, 1–8, doi:10.1088/1748-9326/11/5/055007. http://dx.doi.org/10.1088/1748-9326/11/5/055007.

Havlík, P., and Coauthors, 2015: *Climate Change Impacts and Mitigation in the Developing World - An Integrated Assessment of the Agriculture and Forestry Sectors*. 54 pp.

Hejazi, M. I., and Coauthors, 2015: 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. *Proc. Natl. Acad. Sci. U. S. A.*, **112**, doi:10.1073/pnas.1421675112.

Herold, N., L. Alexander, D. Green, and M. Donat, 2017: Greater increases in temperature extremes in low versus high income countries. *Environ. Res. Lett.*, **12**, 34007, doi:10.1088/1748-9326/aa5c43. http://stacks.iop.org/1748-9326/12/i=3/a=034007.

Hertel, T. W., M. B. Burke, and D. B. Lobell, 2010: The poverty implications of climate-induced crop yield changes by 2030. *Glob. Environ. Chang.*, **20**, 577–585, doi:10.1016/j.gloenvcha.2010.07.001. http://dx.doi.org/10.1016/j.gloenvcha.2010.07.001.

Hess, J. J., J. Z. Mcdowell, and G. Luber, 2012: Review Integrating Climate Change Adaptation into Public Health Practice: Using. *Environ. Health Perspect.*, **120**, 171–179.

Hezri, A. A., and R. Ghazali, 2012: *A fair green economy*.

Hochman, Z., D. Gobbert, and H. Horan, 2016: Climate trends account for stalled wheat yields in Australia since 1990. *Unpublished*, 1–11, doi:10.1111/gcb.13604.

Holden, E., K. Linnerud, and D. Banister, 2015: The Imperatives of Sustainable Development. *Sustain. Dev.*, doi:10.1002/sd.1647.

Howell, R. A., 2013: It's not (just) "'the environment, stupid!'" Values, motivations, and routes to engagement of people adopting lower-carbon lifestyles. *Glob. Environ. Chang.*, **23**, 281–290, doi:10.1016/j.gloenvcha.2012.10.015. http://dx.doi.org/10.1016/j.gloenvcha.2012.10.015.

Hulme, M., 2016: 1.5 °C and climate research after the Paris Agreement. *Nat. Clim. Chang.*, **6**, 222–224, doi:10.1038/nclimate2939. http://www.nature.com/doifinder/10.1038/nclimate2939.

Hussein, Z., T. Hertel, and A. Golub, 2013: Climate change mitigation policies and poverty in developing countries. *Environ. Res. Lett.*, **8**, 35009, doi:10.1088/1748-9326/8/3/035009. http://stacks.iop.org/1748-9326/8/i=3/a=035009?key=crossref.98ac4b7e4a9ccd178df27ec1324bdf58.

Huxham, M., L. Emerton, J. Kairo, F. Munyi, H. Abdirizak, T. Muriuki, F. Nunan, and R. A. Briers, 2015: Applying Climate Compatible Development and economic valuation to coastal management: A case study of Kenya's mangrove forests. *J. Environ. Manage.*, **157**, 168–181, doi:10.1016/j.jenvman.2015.04.018. http://dx.doi.org/10.1016/j.jenvman.2015.04.018.

ICSU and ISSC, 2015: *Review of Targets for the Sustainable Development Goals: The Science Perspective*. 21-24 pp. http://www.icsu.org/publications/reports-and-reviews/review-of-targets-for-the-sustainable-development-goals-the-science-perspective-2015/SDG-Report.pdf.

Iizumi, T., and N. Ramankutty, 2016: Changes in yield variability of major crops for 1981–2010 explained by climate change. *Environ. Res. Lett.*, **11**, 34003, doi:10.1088/1748-9326/11/3/034003. http://stacks.iop.org/1748-9326/11/i=3/a=034003.

Intergovernmental Panel on Climate Change, 2014: *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the IPCC Fifth Assessment Report*. Cambridge University Press, Cambridge,.

Intergovernmental Panel on Climate Change, ed., 2015: Sustainable Developement and Equity. *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report*, Cambridge University Press, Cambridge, 283–350 https://www.cambridge.org/core/books/climate-change-2014-mitigation-of-climate-change/sustainable-developement-and-equity/0DE16CA149576FBE7251B7FC1EA2EE60.

IPCC, 2014: *Climate Change 2014 - Synthesis Report*. 1-7 pp.

IPCC, 2014: Summary for Policymakers. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 1–32.

IPCC, and Coauthors, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation - SREX Summary for Policymakers*. 1-19 pp.

Irvin, Renée A. and Stansbury, J., 2004: Citizen Participation in Decision Making: Is It Worth the Effort? *Public Amin. Rev.*, **64**, 1540–6210, doi:10.1111/j.1540-6210.2004.00346.x.

ISSC, IDS, and UNESCO, 2016: *World Social Science Report 2016, Challenging Inequalities: Pathways to a Just World*. Paris,.

Ivanic, M., and W. Martin, 2014: *Short- and long-run impacts of food price changes on poverty*. 1-43 pp. http://documents.worldbank.org/curated/en/2014/08/20131428/short--long-run-impacts-food-price-changes-poverty.

Ivanic, M., W. Martin, and H. Zaman, 2012: Estimating the short-run poverty impacts of the 2010-11 surge in food prices. *World Dev.*, **40**, 2302–2317, doi:10.1016/j.worlddev.2012.03.024. http://dx.doi.org/10.1016/j.worlddev.2012.03.024.

Ivanova, M., 2016: Good COP, Bad COP: Climate Reality after Paris. *Glob. Policy*, **7**, doi:10.1111/1758-5899.12370.

Jakob, M., and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.*, **11**, 104010, doi:10.1088/1748-9326/11/10/104010. http://stacks.iop.org/1748-9326/11/i=10/a=104010?key=crossref.4cd77602bc9540b790e45408383c5286.

Jakob, M., J. C. Steckel, S. Klasen, J. Lay, N. Grunewald, I. Martínez-Zarzoso, S. Renner, and O. Edenhofer, 2014: Feasible mitigation actions in developing countries. *Nat. Clim. Chang.*, **4**, 961–968, doi:10.1038/nclimate2370. http://www.nature.com/nclimate/journal/v4/n11/full/nclimate2370.html#supplementary-information%5Cnhttp://dx.doi.org/10.1038/nclimate2370.

Jensen, R., 2000: Agricultural volatility and investments in children. *Am. Econ. Rev.*, **90**, 399–404.

Johansson, E. L., M. Fader, J. W. Seaquist, and K. A. Nicholas, 2016: Green and blue water demand from large-scale land acquisitions in Africa. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, 11471–11476, doi:10.1073/pnas.1524741113. http://www.ncbi.nlm.nih.gov/pubmed/27671634 (Accessed March 22, 2017).

Johnson, N., V. Krey, D. L. McCollum, S. Rao, K. Riahi, and J. Rogelj, 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change*, **90**, 89–102, doi:10.1016/j.techfore.2014.02.028. http://dx.doi.org/10.1016/j.techfore.2014.02.028.

Jones, C. D., and Coauthors, 2016: Simulating the Earth system response to negative emissions. *Environ. Res. Lett.*, **11**, 95012, doi:10.1088/1748-9326/11/9/095012. http://stacks.iop.org/1748-9326/11/i=9/a=095012?key=crossref.6b5747055a178d1c59ffa940adb33091.

Kanengoni, A., 2015: Unpaid care work and climate resilient sustainable agriculture: are integrated apporaches possible? http://www.osisa.org/pt-br/node/5555 (Accessed March 27, 2017).

Karmalkar, A. V., and Coauthors, 2017: Consequences of Global Warming of 1.5 °C and 2 °C for Regional Temperature and Precipitation Changes in the Contiguous United States. *PLoS One*, **12**, e0168697, doi:10.1371/journal.pone.0168697. http://dx.plos.org/10.1371/journal.pone.0168697.

KC, S., and W. Lutz, 2014: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004. http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Kelley, C. P., S. Mohtadi, M. A. Cane, R. Seager, and Y. Kushnir, 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Natl. Acad. Sci.*, **112**, 3241–3246, doi:10.1073/pnas.1421533112. http://www.pnas.org/content/112/11/3241.abstract.

Keohane, R. O., and D. G. Victor, 2016: Cooperation and discord in global climate policy. *Nat. Clim. Chang.*, **6**, doi:10.1038/nclimate2937.

Khadka, M., S. Karki, B. S. Karky, R. Kotru, and K. B. Darjee, 2014: Gender Equality Challenges to the REDD+ Initiative in Nepal. *Mt. Res. Dev.*, **34**, 197–207, doi:10.1659/MRD-JOURNAL-D-13-00081.1. http://www.bioone.org/doi/abs/10.1659/MRD-JOURNAL-D-13-00081.1.

Kinley, R., 2017: Climate change after Paris: from turning point to transformation. *Clim. Policy*, **17**, doi:10.1080/14693062.2016.1191009.

Knopf, B., S. Fuss, G. Hansen, F. Creutzig, J. Minx, and O. Edenhofer, 2017: From Targets to Action: Rolling up our Sleeves after Paris. *Glob. Challenges*, 1600007, doi:10.1002/gch2.201600007. http://doi.wiley.com/10.1002/gch2.201600007.

Knutti, R., J. Rogelj, J. Sedláček, and E. M. Fischer, 2015: A scientific critique of the two-degree climate change target. *Nat. Geosci.*, **9**, 13–18, doi:10.1038/ngeo2595. http://dx.doi.org/10.1038/ngeo2595.

Kok, M., B. Metz, J. Verhagen, and S. Van Rooijen, 2008: Integrating development and climate policies: national and international benefits. *Clim. Policy*, **8**, 103–118, doi:10.3763/cpol.2007.0436.

Kolstad, E. W., and K. A. Johansson, 2011: Uncertainties associated with quantifying climate change impacts on human health: A case study for diarrhea. *Environ. Health Perspect.*, **119**, 299–305, doi:10.1289/ehp.1002060.

Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Clim. Change*, **122**, 401–414, doi:10.1007/s10584-013-0971-5.

Kwadijk, J. C. J., and Coauthors, 2010: Using adaptation tipping points to prepare for climate change and sea level rise: A case study in the Netherlands. *Wiley Interdiscip. Rev. Clim. Chang.*, **1**, 729–740, doi:10.1002/wcc.64.

Kwakkel, J., W. Walker, and M. Haasnoot, 2016: Coping with the Wickedness of Public Policy Problems: Approaches for Decision Making under Deep Uncertainty. *J. Water Resour. Plan. Manag.*, **142**, 1816001, doi:10.1061/(ASCE)WR.1943-5452.0000626. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000626.

Larson, A. M., T. Dokken, and A. E. Duchelle, 2014: The role of women in early REDD+ implementation. *REDD+ Gr. A case B. subnational Initiat. across globe*, **17**, 440–441, doi:10.1505/146554815814725031.

Laville, J.-L., 2015: Social and solidarity economy in historical perspective. *Social and Solidarity Economy: Beyond the Fringe?*, P. Utting, Ed., The University of Chicago Press, Chicago.

Lèbre, E., and L. Rovere, 2015: Transforming Development Pathways in Brazil : Towards a Low Carbon Economy 1.

Lechtenboehmer, S., and K. Knoop, 2017: *Realising long-term transitions towards low carbon societies*. 53-91 pp.

Lélé, S. M., 1991: Sustainable development: A critical review. *World Dev.*, **19**, 607–621, doi:10.1016/0305-750X(91)90197-P. http://www.sciencedirect.com/science?_ob=ArticleListURL&_method=list&_ArticleListID=-1182388579&_sort=r&_st=13&view=c&md5=b7a7ffdeff8f2076c768b4696b2a24d7&searchtype=a (Accessed April 13, 2017).

Lesk, C., P. Rowhani, and N. Ramankutty, 2016: Influence of extreme weather disasters on global crop production. *Nature*, **529**, 84–87, doi:10.1038/nature16467. http://www.nature.com/doifinder/10.1038/nature16467.

Lewis, M., and P. Conaty, 2012: *The resilience imperative: Cooperative transitions to a steady-state economy*. New Society Publishers, Gabriola Island, British Colombia,.

Li, Y., W. Ye, M. Wang, and X. Yan, 2009: Climate change and drought: a risk assessment of crop-yield impacts. *Clim. Res.*, **39**, 31–46, doi:10.3354/cr00797. http://www.int-res.com/abstracts/cr/v39/n1/p31-46/.

Lindner, F., 2013: Does Saving Increase the Supply of Credit? A Critique of Loanable Funds Theory. *IMK Work. Pap.*, 1–26.

Liu, J., F. Ma, and Y. Li, 2011: The effect of anthropogenic heat on local heat island intensity and the performance of air conditioning systems. *Adv. Mater. Res.*, **250**–**253**, 2975–2978, doi:10.4028/www.scientific.net/AMR.250-253.2975.

Liu, Q., A. Gu, F. Teng, R. Song, and Y. Chen, 2017: Peaking China's CO2 Emissions: Trends to 2030 and Mitigation Potential. *Energies*, **10**, 209, doi:10.3390/en10020209. http://www.mdpi.com/1996-1073/10/2/209.

Llavador, H., J. E. Roemer, and J. Silvestre, 2015: *Sustainability for a warming planet*. Harvard University Press, Cambridge Massachusetts,.

Lobell, D. B., and C. Tebaldi, 2014: Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. *Environ. Res. Lett.*, **9**, 74003, doi:10.1088/1748-9326/9/7/074003. http://stacks.iop.org/1748-9326/9/i=7/a=074003?key=crossref.8e7c20bfe100e9419ae3b01c9a85737c.

Lubchenco, J., E. B. Cerny-Chipman, J. N. Reimer, and S. A. Levin, 2016: The right incentives enable ocean sustainability successes and provide hope for the future. *Proc. Natl. Acad. Sci. U. S. A.*, **113**, doi:10.1073/pnas.1604982113.

Lubell, M., J. M. Mewhirter, R. Berardo, and J. T. Scholz, 2016: Transaction Costs and the Perceived Effectiveness of Complex Institutional Systems. *Public Adm. Rev.*, doi:10.1111/puar.12622.

Luderer, G., R. C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, and O. Edenhofer, 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033, doi:10.1088/1748-9326/8/3/034033. http://stacks.iop.org/1748-9326/8/i=3/a=034033?key=crossref.68299324c711aa38b9eb1d10cb1df7ec.

MacKinnon, D., and K. D. Derickson, 2013: From resilience to resourcefulness: A critique of resilience policy and activism. *Prog. Hum. Geogr.*, **37**, 253–270.

Magnan, A. K., and Coauthors, 2016: Implications of the Paris agreement for the ocean. *Nat. Clim. Chang.*, **6**, 732–735, doi:10.1038/nclimate3038. http://www.nature.com/doifinder/10.1038/nclimate3038.

Mahlstein, I., R. Knutti, S. Solomon, and R. W. Portmann, 2011: Early onset of significant local warming in low latitude countries. *Environ. Res. Lett.*, **6**, 34009, doi:10.1088/1748-9326/6/3/034009.

Makina, A. ., and T. . Moyo, 2016: Mind the gap: institutional considerations for gender-inclusive climate change policy in Sub-Saharan Africa. *Local Environ.*, **9839**, 1–13, doi:10.1080/13549839.2016.1189407. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84973138223&partnerID=40&md5=183f2c7611bfeefd7faf5e0322e0bd56.

Maor, M., J. Tosun, and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *J. Environ. Policy Plan.*, doi:10.1080/1523908X.2017.1281730. http://dx.doi.org/10.1080/1523908X.2017.1281730.

Mason, K., and M. Whitehead, 2012: Transition urbanism and the contested politics of ethical place making. *Antipode*, **44**, 493–516.

Mayrhofer, J. P., and J. Gupta, 2016: The science and politics of co-benefits in climate policy. *Environ. Sci. Policy*, **57**, 22–30, doi:10.1016/j.envsci.2015.11.005. http://dx.doi.org/10.1016/j.envsci.2015.11.005.

McDonough, W., 2016: Carbon is not the Enemy. *Nature*, **539**, 349–351.

McGlade, C., and P. Ekins, 2015: The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, **517**, 187–190, doi:10.1038/nature14016. http://www.nature.com/doifinder/10.1038/nature14016%5Cnpapers2://publication/doi/10.1038/nature14016.

McGranahan, G., D. L. Balk, and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban.*, **19**, 17–37, doi:10.1177/0956247807076960. http://eau.sagepub.com/cgi/doi/10.1177/0956247807076960.

McMurtry, J.-J., 2013: Prometheus, Trojan Horse or Frankenstein? The Social and Solidarity Economy as Community Creation, Market Wedge, or State Monster (Draft). *UNRISD Conference" Potential and Limits of Social and Solidarity Economy*, UNRISD.

MEA, 2005: *Ecosystems and human well-being: our human planet: summary for decision makers*. Island Press, Washington DC,.

Meadowcroft, J., 2011: Engaging with the politics of sustainability transitions. *Environ. Innov. Soc. Transitions*, **1**, 70–75, doi:10.1016/j.eist.2011.02.003. http://dx.doi.org/10.1016/j.eist.2011.02.003.

Mehmood, A., 2016: Of resilient places: planning for urban resilience. *Eur. Plan. Stud.*, **24**, 407–419.

Melamed, C., and E. Samman, 2013: Equity, Inequality And Human Development in a Post-2015 Framework. *UNDO Hum. Dev. Rep. Ofice Res. Pap.*, 1–35.

Mitchell, T., and S. Maxwell, 2010: Defining climate compatible development. *Policy Br.*, 6. www.cdkn.org.

Morseletto, P., F. Biermann, and P. Pattberg, 2016: Governing by targets: reductio ad unum and evolution of the two-degree climate target. *Int. Environ. Agreements Polit. Law Econ.*, 1–22, doi:10.1007/s10784-016-9336-7.

Mugambiwa, S. S., and H. M. Tirivangasi, 2017: Climate change: A threat towards achieving “sustainable development goal number two” (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) in South Africa. *Jamba J. Disaster Risk Stud.*, **9**, doi:10.4102/jamba.v9i1.350.

Muller, C., K. Waha, A. Bondeau, and J. Heinke, 2014: Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. *Glob. Chang. Biol.*, **20**, 2505–2517, doi:10.1111/gcb.12586.

Mulugetta, Y., and F. Urban, 2010: Deliberating on low carbon development. *Energy Policy*, **38**, 7546–7549, doi:10.1016/j.enpol.2010.05.049. http://dx.doi.org/10.1016/j.enpol.2010.05.049.

Munang, R., I. Thiaw, K. Alverson, M. Mumba, J. Liu, and M. Rivington, 2013: Climate change and Ecosystem-based Adaptation: A new pragmatic approach to buffering climate change impacts. *Curr. Opin. Environ. Sustain.*, **5**, doi:10.1016/j.cosust.2012.12.001.

Muradian, R., and Coauthors, 2013: Payments for ecosystem services and the fatal attraction of win-win solutions. *Conserv. Lett.*, **6**, 274–279.

Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environ. Res. Lett.*, **11**, 1–9, doi:10.1088/1748-9326/11/9/095004. http://dx.doi.org/10.1088/1748-9326/11/9/095004.

Mushove, P., and C. Vogel, 2005: Heads or tails? Stakeholder analysis as a tool for conservation area management. *Glob. Environ. Chang.*, **15**, 184–198, doi:10.1016/j.gloenvcha.2004.12.008.

Muttarak, R., and W. Lutz, 2014: Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecol. Soc.*, **19**, doi:10.5751/ES-06476-190142.

Myers, S. S., M. R. Smith, S. Guth, C. D. Golden, B. Vaitla, N. D. Mueller, A. D. Dangour, and P. Huybers, 2017: Climate Change and Global Food Systems : Potential Impacts on Food Security and Undernutrition. *Annu. Rev. Public Health*, 1–19, doi:10.1146/annurev-publhealth-031816-044356.

Naess, L. O., P. Newell, A. Newsham, J. Phillips, J. Quan, and T. Tanner, 2015: Climate policy meets national development contexts: Insights from Kenya and Mozambique. *Glob. Environ. Chang.*, **35**, 534–544, doi:10.1016/j.gloenvcha.2015.08.015. http://dx.doi.org/10.1016/j.gloenvcha.2015.08.015.

Nelson, D. R., M. C. Lemos, H. Eakin, and Y.-J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environ. Res. Lett.*, **11**, 94011, doi:10.1088/1748-9326/11/9/094011. http://stacks.iop.org/1748-

9326/11/i=9/a=094011?key=crossref.04423c7692ee03c09b07c3c0e8322f4b.

Nelson, G. C., and Coauthors, 2014: Climate change effects on agriculture: economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3274–3279, doi:10.1073/pnas.1222465110. http://www.pnas.org/content/111/9/3274.full.pdf.

Newell, P., J. Phillips, A. Pueyo, E. Kirumba, N. Ozor, and K. Urama, 2014: *The Political Economy of Low Carbon Energy in Kenya*. 38 pp. http://www.ids.ac.uk/publication/the-political-economy-of-low-carbon-energy-in-kenya%5Cnhttp://opendocs.ids.ac.uk/opendocs/bitstream/handle/123456789/4049/Wp445.pdf?sequence=5.

Nilsson, M., D. Griggs, and M. Visback, 2016: Map the interactions between Sustainable Development Goa. *Nature*, **534**, 320–322, doi:10.1038/534320a. http://dx.doi.org/10.1787/.

Nilsson, M., D. Griggs, M. Visbeck, and C. Ringler, 2016: *A draft framework for understanding SDG interactions*.

Noble, I., S. Huq, and Y. Anokhin, 2014: Adaptation needs and options. *IPCC, AR5, WGII*, 659–708.

Nussbaum, M. C., 2007: *Frontiers of justice: disability, nationality, species membership*. Harvard University Press, Cambridge Massachusetts,.

O'Brien, K. L., 2016: Climate change and social transformations: is it time for a quantum leap? *Wiley Interdiscip. Rev. Clim. Chang.*, **7**, 618–626, doi:10.1002/wcc.413.

O'Brien, K., and Coauthors, 2013: You say you want a revolution? Transforming education and capacity building in response to global change. *Environ. Sci. Policy*, **28**, 48–59, doi:10.1016/j.envsci.2012.11.011. http://dx.doi.org/10.1016/j.envsci.2012.11.011.

OECD, 2016: *Better Policies for Sustainable Development 2016 A New Framework for policy coherence*. Paris, 295 pp.

OECD, 2015: *OECD environmental performance reviews: Brazil 2015*.

Okorosobo, T., F. Okorosobo, G. Mwabu, N. J. Orem, and M. J. Kirigia, 2011: Economic Burden of Malaria in six Countries of Africa. *Eur. J. Bus. Manag.*, **3**, 42–63.

Olsson, L., M. Opondo, P. Tschakert, A. Agrawal, S. H. Eriksen, S. Ma, L. N. Perch, and S. A. Zakieldeen, 2014: Livelihoods and Poverty. *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field et al., Eds., Cambridge University Press, Cambridge and New York, 793–832 http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap13_FINAL.pdf.

O'Neill, B. C., and Coauthors, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004. http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Oppenheimer, M., M. Campos, and R. Warren, 2014: Emergent risks and key vulnerabilities. *IPCC, AR5, WGII*, 659–708.

Oshiro, K., M. Kainuma, and T. Masui, 2016: Assessing decarbonization pathways and their implications for energy security policies in Japan. *Clim. Policy*, **16**, S63–S77, doi:10.1080/14693062.2016.1155042. http://www.tandfonline.com/doi/full/10.1080/14693062.2016.1155042 (Accessed March 23, 2017).

Pancost, R., 2016: Cities lead on climate change. *Nat. Geosci.*, **9**, 264–266.

Patterson, J., and Coauthors, 2015: Exploring the governance and politics of transformations towards sustainability. *Environ. Innov. Soc. Transitions*, 1–16, doi:10.1016/j.eist.2016.09.001. http://dx.doi.org/10.1016/j.eist.2016.09.001.

Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Clim. Change*, **133**, 113–127, doi:10.1007/s10584-014-1303-0.

Peters, G. P., R. M. Andrew, J. G. Canadell, S. Fuss, R. B. Jackson, J. I. Korsbakken, C. Le Quéré, and N. Nakicenovic, 2017: Key indicators to track current progress and future ambition of the Paris Agreement. *Nat. Clim. Chang.*, doi:10.1038/nclimate3202. http://www.nature.com/doifinder/10.1038/nclimate3202.

Pollard, S., and D. du Toit, 2011: Towards Adaptive Integrated Water Resources Management in Southern Africa: The Role of Self-organisation and Multi-scale Feedbacks for Learning and Responsiveness in the Letaba and Crocodile Catchments. *Water Resour. Manag.*, **25**, 4019–4035, doi:10.1007/s11269-011-9904-0.

Pollard, S., D. du Toit, and H. Biggs, 2011: River management under transformation: The emergence of strategic adaptive management of river systems in the kruger national park. *Koedoe*, **53**, 1–14, doi:10.4102/koedoe.v53i2.1011.

Punton, A., E. J. Crossley, N. R. Matthews, and S. C. Walpole, 2017: Protecting health from climate change requires concerted action and radical approaches: A discussion of recent progress in international climate negotiations. *Int. J. Occup. Environ. Med.*, **8**.

Rao, N. D., K. Riahi, and A. Grubler, 2014: Climate impacts of poverty eradication. *Nat. Clim. Chang.*, **4**, doi:10.1038/nclimate2340.

Rasul, G., and B. Sharma, 2016: The nexus approach to water–energy–food security: an option for adaptation to climate change. *Clim. Policy*, **16**, 682–702, doi:10.1080/14693062.2015.1029865. http://www.tandfonline.com/doi/full/10.1080/14693062.2015.1029865%5Cnhttp://dx.doi.org/10.1080/14693062.2015.1029865%5Cnhttp://www.tandfonline.com/doi/full/10.1080/14693062.2015.1029865.

Raworth, K., 2012: A Safe and Just Space For Humanity: Can we live within the Doughnut? *Nature*, **461**, 1–26,

doi:10.5822/978-1-61091-458-1. http://www.oxfam.org/en/grow/policy/safe-and-just-space-humanity.
Reckien, D., F. Creutzig, B. Fernandez, B. Lwasa, M. Tovar-Restrepo, D. McEvoy, and D. Sattherthwaite, 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environ. Urban.*, 95624781667777, doi:10.1177/0956247816677778. http://journals.sagepub.com/doi/10.1177/0956247816677778 (Accessed March 22, 2017).
Rescalvo, M., M. Lasa, N. D'Silva, R. Barrios, L. Sommaripa, S. Scholz, and L. Sugar, 2013: "Low carbon city development" (LCCD) as a strategy for sustainable cities: The case of Rio de Janeiro, Brazil. *Int. J. Technol. Manag. Sustain. Dev.*, **12**, 261–280, doi:10.1386/tmsd.12.3.261_1. http://www.scopus.com/inward/record.url?eid=2-s2.0-84893349691&partnerID=tZOtx3y1.
Resurrecci??n, B. P., 2013: Persistent women and environment linkages in climate change and sustainable development agendas. *Womens. Stud. Int. Forum*, **40**, 33–43, doi:10.1016/j.wsif.2013.03.011. http://dx.doi.org/10.1016/j.wsif.2013.03.011.
Riahi, K., and Coauthors, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.
Rietig, K., 2013: Sustainable Climate Policy Integration in the European Union. *Environ. Policy Gov.*, **23**, 297–310, doi:10.1002/eet.1616. http://doi.wiley.com/10.1002/eet.1616 (Accessed March 24, 2017).
Robiou, Y., D. Pont, M. L. Jeeery, J. Gütschow, J. Rogelj, P. Christoo, and M. Meinshausen, 2017: Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Chang.*, **7**, 38–43, doi:10.1038/NCLIMATE3186.
Rockström, J., O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H. J. Schellnhuber, 2017: A roadmap for rapid decarbonization. *Science (80-.).*, **355**, 1269–1271. http://science.sciencemag.org/content/355/6331/1269.abstract.
Rockström, J., and Coauthors, 2016: Earth ' s Future The world ' s biggest gamble Earth ' s Future. *Earth's Futur.*, **4**, 465–470, doi:10.1002/2016EF000392.Received.
Rockström, J., and Coauthors, 2009: A safe operating space for humanity. *Nature*, **461**, 472–475.
Rockström, J., and Coauthors, 2009: Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.*, **14**, art32, doi:10.5751/ES-03180-140232. http://www.ecologyandsociety.org/vol14/iss2/art32/ (Accessed March 24, 2017).
Rockström, J., and Coauthors, 2016: Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, 1–14, doi:10.1007/s13280-016-0793-6.
Rogelj, J., and Coauthors, 2016: Perspective : Paris Agreement climate proposals need boost to keep warming well below 2 ° C. *Nat. Clim. Chang.*, **534**, 631–639, doi:10.1038/nature18307. http://0-www.nature.com.wam.city.ac.uk/nature/journal/v534/n7609/pdf/nature18307.pdf.
Rogelj, J., and Coauthors, 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Chang.*, **1**, 413–418, doi:10.1038/nclimate1258. http://dx.doi.org/10.1038/nclimate1258.
Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi, 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.*, **5**, 519–527, doi:10.1038/nclimate2572. http://www.nature.com/doifinder/10.1038/nclimate2572.
Rogelj, J., D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature*, **493**, 79–83, doi:http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1758.html#supplementary-information. http://dx.doi.org/10.1038/nclimate1758.
Rogelj, J., M. Schaeffer, and B. Hare, 2015: *Timetables for Zero Emissions and 2050 Emissions Reductions: State of the Science for the ADP Agreement*. 2 pp.
Roine, J., and D. Waldenström, 2015: Long-run trends in the distribution of income and wealth. *Handbook of income distribution*, A.B. Atkinson and F. Bourguignon, Eds., North-Holland, Amsterdam.
Roman, P., and G. Thiry, 2016: The inclusive wealth index. A critical appraisal. *Ecol. Econ.*, **124**, doi:10.1016/j.ecolecon.2015.12.008.
Rosenzweig, C., and Coauthors, 2017: Assessing inter-sectoral climate change risks: the role of ISIMIP. *Environ. Res. Lett.*, **12**, 10301, doi:10.1088/1748-9326/12/1/010301. http://stacks.iop.org/1748-9326/12/i=1/a=010301?key=crossref.8b61ee6c8aa6d3b1b3ec37505238fb98.
Rosenzweig, C., and Coauthors, 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 3268–3273, doi:10.1073/pnas.1222463110. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3948251&tool=pmcentrez&rendertype=abstract.
Roy, J., D. Ganguly, and D. Chakravarty, 2016: Low carbon green growth strategies and sustainable development for mega cities: A case study of Kolkata. *Amity J. Econ.*, **1**, 73–86.
Rozenberg, J., A. Vogt-schilb, and S. Hallegatte, 2014: *Transition to clean capital, irreversible investment and stranded assets*. 1-25 pp. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2433812.
Sachs, J., G. Schmidt-Traub, C. Kroll, D. Durand-Delacre, and K. Teksoz, 2016: *SDG Index and Dashboards - Global Report*. New York,.

Saito, N., 2013: Mainstreaming climate change adaptation in least developed countries in South and Southeast Asia. *Mitig. Adapt. Strateg. Glob. Chang.*, **18**, 825–849, doi:10.1007/s11027-012-9392-4.

Sathaye, J., and Coauthors, 2007: Sustainable development and mitigation. 692–743. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch12.html.

Schaeffer, M., L. Gohar, E. Kriegler, J. Lowe, K. Riahi, and D. van Vuuren, 2015: Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technol. Forecast. Soc. Change*, **90**, 257–268, doi:10.1016/j.techfore.2013.09.013. http://dx.doi.org/10.1016/j.techfore.2013.09.013.

Schaeffer, M., W. Hare, S. Rahmstorf, and M. Vermeer, 2012: Long-term sea-level rise implied by 1.5 degree C and 2 degree C warming levels. *Nat. Clim. Chang.*, **2**, 1–4, doi:10.1038/nclimate1584. http://dx.doi.org/10.1038/nclimate1584%5Cnpapers2://publication/doi/10.1038/nclimate1584.

Schaeffer, M., J. Rogelj, N. Roming, F. Sferra, B. Hare, and O. Serdeczny, 2015: *Feasibility of limiting warming to 1.5 and 2°C.*

Schandl, H., and Coauthors, 2016: Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. *J. Clean. Prod.*, **132**, doi:10.1016/j.jclepro.2015.06.100.

Schellnhuber, H. J., S. Rahmstorf, and R. Winkelmann, 2016: Why the right climate target was agreed in Paris. *Nat. Clim. Chang.*, **6**, 649–653, doi:10.1038/nclimate3013. http://dx.doi.org/10.1038/nclimate3013%5Cnhttp://10.1038/nclimate3013.

Schleussner, C. F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. *Earth Syst. Dyn.*, **7**, 327–351, doi:10.5194/esd-7-327-2016.

Schlosberg, D., and L. B. Collins, 2014: From environmental to climate justice: Climate change and the discourse of environmental justice. *Wiley Interdiscip. Rev. Clim. Chang.*, **5**, 359–374, doi:10.1002/wcc.275.

Schwarzer, H., C. Van Panhuys, and K. Diekmann, 2016: Protecting people and the environment: lessons learnt from Brazil's Bolsa Verde, China, Costa Rica, Ecuador, Mexico, South Africa and 56 other experiences.

Sen, A., 2004: Capabilities, Lists, and Public Reason: Continuing the Conversation. *Fem. Econ.*, **10**, 77–80, doi:10.1080/1354570042000315163.

Sen, A., 2001: *Development as freedom*. Oxford University Press, Oxford, UK,.

Seneviratne, S. I., M. G. Donat, A. J. Pitman, R. Knutti, and R. L. Wilby, 2016: Allowable CO2 emissions based on regional and impact-related climate targets. *Nature*, **529**, 477–483. http://dx.doi.org/10.1038/nature16542.

Shaw, A., S. Burch, F. Kristensen, J. Robinson, and A. Dale, 2014: Accelerating the sustainability transition: Exploring synergies between adaptation and mitigation in British Columbian communities. *Glob. Environ. Chang.*, **25**, 41–51, doi:10.1016/j.gloenvcha.2014.01.002.

Shepherd, A., and Coauthors, 2014: The Chronic Poverty Report 2014-2015: The road to zero extreme poverty. 176. https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8834.pdf.

Shove, E., and G. Walker, 2007: CAUTION! Transitions ahead: Politics, practice, and sustainable transition management. *Environ. Plan. A*, **39**, 763–770, doi:10.1068/a39310.

Shrader-Frechette, K., 2007: *Taking action, saving lives: our duties to protect environmental and public health*. Oxford University Press, Oxford, UK,.

Shukla, P., S. Dhar, M. Pathakb, D. Mahadeviab, and A. Garg, 2015: Pathways to deep decarbonization in India. http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_IND.pdf (Accessed March 23, 2017).

Singh, A., M. Syal, S. C. Grady, and S. Korkmaz, 2010: Effects of green buildings on employee health and productivity. *Am. J. Public Health*, **100**, 1665–1668, doi:10.2105/AJPH.2009.180687.

Smith, A., and A. Stirling, 2010: The Politics of Social-ecological Resilience and Sustainable Socio- technical Transitions. *Ecol. Soc.*, **15**, 11, doi:10.5751/ES-04565-170208. http://www.ecologyandsociety.org/vol15/iss1/art11/.

Smith, P., and Coauthors, 2016: Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.*, **6**, 42–50, doi:10.1038/nclimate2870\rhttp://www.nature.com/nclimate/journal/v6/n1/abs/nclimate2870.html#supplementary-information. http://dx.doi.org/10.1038/nclimate2870.

Sovacool, B. K., B.-O. Linnér, and M. E. Goodsite, 2015: The political economy of climate adaptation. *Nat. Clim. Chang.*, **5**, 616–618, doi:10.1038/nclimate2665. http://www.nature.com/doifinder/10.1038/nclimate2665.

Sovacool, B. K., M. Tan Mullins, D. Ockwell, and P. Newell, 2017: Political economy, poverty, and polycentrism in the Global Environment Facility's Least Developed Countries Fund (LDCF) for Climate Change Adaptation. *Third World Q.*, **6597**, 1–23, doi:10.1080/01436597.2017.1282816. https://www.tandfonline.com/doi/full/10.1080/01436597.2017.1282816.

Spaiser, V., S. Ranganathan, R. B. Swain, and J. T. David, 2016: The sustainable development oxymoron : quantifying and modelling the incompatibility of sustainable development goals. *Int. J. Sustain. Dev. World Ecol.*, **0**, 1–14, doi:10.1080/13504509.2016.1235624. http://dx.doi.org/10.1080/13504509.2016.1235624.

Stechow, C. von, and Coauthors, 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annu. Rev. Environ. Resour.*, **40**, 363–394, doi:10.1146/annurev-environ-021113-095626. http://www.annualreviews.org/doi/10.1146/annurev-environ-021113-095626.

Steffen, W., K. Richardson, J. Rockström, S. Cornell, I. Fetzer, E. Bennett, R. Biggs, and S. Carpenter, 2015: Planetary boundaries: Guiding human development on a changing planet. *Science*, **348**, 1217, doi:10.1126/science.aaa9629.
Sterett, C., 2015: *Final evaluation of the Vanuatu NGO Climate Change Adaptation Program Evaluation*.
Stern, N. H., 2007: *The economics of climate change: the Stern review*. Cambridge University Press, Cambridge,.
Stevanović, M., and Coauthors, 2016: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environ. Sci. Technol.*, doi:10.1021/ACS.EST.6B04291.
Striessnig, E., and E. Loichinger, 2015: Future differential vulnerability to natural disasters by level of education. *Vienna Yearb. Popul. Res.*, **13**, 221–240.
Striessnig, E., W. Lutz, and A. G. Patt, 2013: Effects of Educational Attainment on Climate Risk Vulnerability. *Ecol. Soc.*, **18**, doi:10.5751/ES-05252-180116.
Suckall, N., L. C. Stringer, and E. L. Tompkins, 2014: Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. *Ambio*, 34–41, doi:10.1007/s13280-014-0520-0.
Swart, R., and F. Raes, 2007: Making integration of adaptation and mitigation work: mainstreaming into sustainable development policies? *Clim. Policy*, **7**, 288–303, doi:10.1080/14693062.2007.9685657. http://www.tandfonline.com/doi/pdf/10.1080/14693062.2007.9685657?needAccess=true (Accessed March 24, 2017).
Tapsell, S. M., E. Penning-Rowsell, S. Tunstall, and T. Wilson, 2002: Vulnerability to flooding : health. *Phil. Trans. R. Soc. Lond. A*, **360**, 1511–1525.
Termeer, C.J.A.M, A., and M. va. V. A. Dewulf , S.I. Karlsson-Vinkhuyzen , M. Vink, 2016: Coping with the wicked problem of climate adaptation across scales: The Five R Governance Capabilities. *Landsc. Urban Plan.*, **154**, 11–19, doi:10.1016/j.landurbplan.2016.01.007.
The Climate Institute, 2016: *Beyond the limits: Australia in a 1.5-2°C world*.
Thorne, J. H., M. J. Santos, J. Bjorkman, O. Soong, M. Ikegami, C. Seo, and L. Hannah, 2017: Does infill outperform climate-adaptive growth policies in meeting sustainable urbanization goals? A scenario-based study in California, USA. *Landsc. Urban Plan.*, **157**, 483–492, doi:10.1016/j.landurbplan.2016.08.013. http://dx.doi.org/10.1016/j.landurbplan.2016.08.013.
Thornton, T. F., and C. Comberti, 2013: Synergies and trade-offs between adaptation, mitigation and development. *Clim. Change*, 1–14, doi:10.1007/s10584-013-0884-3.
Turnheim, B., F. Berkhout, F. Geels, A. Hof, A. McMeekin, B. Nykvist, and D. van Vuuren, 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob. Environ. Chang.*, **35**, 239–253, doi:10.1016/j.gloenvcha.2015.08.010.
Uittenbroek, C. J., L. B. Janssen-Jansen, and H. A. C. Runhaar, 2013: Mainstreaming climate adaptation into urban planning: Overcoming barriers, seizing opportunities and evaluating the results in two Dutch case studies. *Reg. Environ. Chang.*, **13**, 399–411, doi:10.1007/s10113-012-0348-8.
Uk, R. S. J. T., 2014: and Services Coordinating Lead Authors : Lead Authors : Contributing Authors : Review Editors : 659–708.
UNDP, 2016: *Human Development Report 2016 Human Development for Everyone*.
UNEP, 2016: *The Emissions Gap Report 2016*. Nairobi, 86 pp. http://www.unep.org/pdf/2012gapreport.pdf.
UNESCO and ISSC, 2016: *World Social Science Report World Social Science Report*.
United Nations (UN), 2015: *The Millennium Development Goals Report 2015*. http://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG 2015 rev (July 1).pdf Accessed 25th July 2016.
United Nations Research Institute for Social Development (UNRISD), 2016: *Policy Innovations Transformative Change*.
United Nations, and D. for S. D. Department of Economic and Social Affairs, 2014: *Prototype Global Sustainable Development report*. New Yok, https://sustainabledevelopment.un.org/content/documents/1454Prototype Global SD Report2.pdf (Accessed March 23, 2017).
UNRISD, 2016: *Policy innovations for transformative change: Implementing the 2030 Agenda for Sustainable Development*. Geneva,.
UNTFSSE, 2014: *Social and Solidarity Economy and the challenge of sustainable development: A position paper by the United Nations Inter-Agency Task Force on Social and Solidarity Economy*.
Ürge-Vorsatz, D., S. T. Herrero, N. K. Dubash, and F. Lecocq, 2014: Measuring the Co-Benefits of Climate Change Mitigation. *Annu. Rev. Environ. Resour.*, **39**, 549–582, doi:10.1146/annurev-environ-031312-125456.
Ürge-Vorsatz, D., and Coauthors, 2016: Measuring multiple impacts of low-carbon energy options in a green economy context. *Appl. Energy*, **179**, 1409–1426, doi:10.1016/j.apenergy.2016.07.027.
Utting, P., 2015: *Social and solidarity economy: Beyond the fringe*. Zed Books London, London,.
Van Aelst, K., and N. Holvoet, 2016: Intersections of Gender and Marital Status in Accessing Climate Change Adaptation: Evidence from Rural Tanzania. *World Dev.*, **79**, 40–50, doi:10.1016/j.worlddev.2015.11.003. http://dx.doi.org/10.1016/j.worlddev.2015.11.003.

van Soest, H., and Coauthors, 2015: *Regional low-emission pathways from global models*. Milano,.

van Vuuren, D. P., and Coauthors, 2014: A new scenario framework for Climate Change Research: Scenario matrix architecture. *Clim. Change*, **122**, 373–386, doi:10.1007/s10584-013-0906-1.

van Vuuren, D. P., and Coauthors, 2017: The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Glob. Environ. Chang.*, **42**, 148–152, doi:10.1016/j.gloenvcha.2016.10.009. http://linkinghub.elsevier.com/retrieve/pii/S0959378016301790.

Vargo, J., B. Stone, D. Habeeb, P. Liu, and A. Russell, 2016: The social and spatial distribution of temperature-related health impacts from urban heat island reduction policies. *Environ. Sci. Policy*, **66**, 366–374, doi:10.1016/j.envsci.2016.08.012. http://linkinghub.elsevier.com/retrieve/pii/S1462901116305627.

Vogel, C., I. Koch, and K. Van Zyl, 2010: "A Persistent Truth"—Reflections on Drought Risk Management in Southern Africa. *Weather. Clim. Soc.*, **2**, 9–22, doi:10.1175/2009WCAS1017.1.

Vogel, C., S. C. Moser, R. E. Kasperson, and G. D. Dabelko, 2007: Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Glob. Environ. Chang.*, **17**, 349–364, doi:10.1016/j.gloenvcha.2007.05.002.

von Stechow, C., and Coauthors, 2016: 2°C and SDGs: United they stand, divided they fall? *Environ. Res. Lett.*, **11**, doi:10.1088/1748-9326/11/3/034022.

Wainstein, M. E., and A. G. Bumpus, 2015: Business models as drivers of the low carbon power system transition: A multi-level perspective. *J. Clean. Prod.*, **126**, 572–585, doi:10.1016/j.jclepro.2016.02.095.

Wallimann, I., 2014: Social and solidarity economy for sustainable development: its premises--and the Social Economy Basel example of practice. *Int. Rev. Sociol.*, **24**, 48–58.

Wamsler, C. ;, C. ; Luederitz, E. Brink, C. Wamsler, and C. Luederitz, 2014: Local levers for change: Mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. *Glob. Environ. Chang.*, **29**, 189–201, doi:10.1016/j.gloenvcha.2014.09.008. http://portal.research.lu.se/portal/files/1495427/7512402.pdf (Accessed March 24, 2017).

Wang, L., P. L. Patel, S. Yu, B. Liu, J. McLeod, L. E. Clarke, and W. Chen, 2016: Win-Win strategies to promote air pollutant control policies and non-fossil energy target regulation in China. *Appl. Energy*, **163**, 244–253, doi:10.1016/j.apenergy.2015.10.189. http://dx.doi.org/10.1016/j.apenergy.2015.10.189.

Wartenburger, R., M. Hirschi, M. G. Donat, P. Greve, A. J. Pitman, and S. I. Seneviratne, 2017: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geosci. Model Dev. Discuss.*, 1–30, doi:10.5194/gmd-2017-33. http://www.geosci-model-dev-discuss.net/gmd-2017-33/.

Webster, P. J., and J. Jian, 2011: Environmental prediction, risk assessment and extreme events: adaptation strategies for the developing world. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **369**, 4768–4797, doi:10.1098/rsta.2011.0160.

Weiss, M., and C. Cattaneo, 2017: Degrowth – Taking Stock and Reviewing an Emerging Academic Paradigm. *Ecol. Econ.*, doi:10.1016/j.ecolecon.2017.01.014. http://linkinghub.elsevier.com/retrieve/pii/S0921800916305900.

Welsch, M., and Coauthors, 2014: Adding value with CLEWS - Modelling the energy system and its interdependencies for Mauritius. *Appl. Energy*, **113**, 1434–1445, doi:10.1016/j.apenergy.2013.08.083.

Werners, S. E., E. Van Slobbe, T. Bölscher, A. Oost, S. Pfenninger, G. Trombi, and M. Bindi, 2015: Turning points in climate change adaptation. *Ecol. Soc.*, **20**.

Westholm, L., and S. Arora-Jonsson, 2015: Defining Solutions, Finding Problems: Deforestation, Gender, and REDD+ in Burkina Faso. *Conserv. Soc.*, **13**, 189, doi:10.4103/0972-4923.164203. http://www.conservationandsociety.org/text.asp?2015/13/2/189/164203.

Winer, M., H. Murphy, and H. Ludwig, 2012: *Payment for ecosystem services markets on Aboriginal land in Cape York Pensinsula: potential and constraints*. United Nations Research Institute for Social Development,.

Winkler, H., A. Boyd, M. Torres Gunfaus, and S. Raubenheimer, 2015: Reconsidering development by reflecting on climate change. *Int. Environ. Agreements Polit. Law Econ.*, **15**, 369–385, doi:10.1007/s10784-015-9304-7.

Winsemius, H. C., B. Jongman, T. I. E. Veldkamp, S. Hallegatte, M. Bangalore, and P. J. Ward, 2015: *Disaster risk, climate change, and poverty : assessing the global exposure of poor people to floods and droughts*. 1-35 pp. http://documents.worldbank.org/curated/en/2015/11/25250857/disaster-risk-climate-change-poverty-assessing-global-exposure-poor-people-floods-droughts.

Wise, R. M., I. Fazey, M. Stafford Smith, S. E. Park, H. C. Eakin, E. R. M. Archer Van Garderen, and B. Campbell, 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ. Chang.*, **28**, 325–336, doi:10.1016/j.gloenvcha.2013.12.002. http://dx.doi.org/10.1016/j.gloenvcha.2013.12.002.

Wiseman, J. and S. A., 2017: The Degrowth Imperative: Reducing energy and resource consumption as an essentail component in achieving carbon budget targets. *Transitioning to a Post Carbon Society*, 87–108.

Wolf, S., C. Jaeger, J. Mielke, F. Schütze, G. Climate, and R. Rosen, 2017: Framing 1.5°C - Turning an investment challenge into a green growth opportunity. 1–10.

Woodward, A., G. Lindsay, and S. Singh, 2011: Adapting to climate change to sustain health. *Wiley Interdiscip. Rev. Clim. Chang.*, **2**, 271–282, doi:10.1002/wcc.103.

World Commission on Environment and Development, 1987: *Our Common Future*. 400 pp. http://www.un-documents.net/wced-ocf.htm.

World Health Organisation, and others, 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. World Health Organization,.

World Health Organization, 2003: *Climate change and human health: risks and responses*. A.J. McMichael, D.H. Campbell-Lendrum, C.F. Corvalan, A.K. Githeko, J.D. Scheraga, and A. Woodward, Eds. World Health Organization, Geneva,.

World Health Organization, 2002: *The world health report 2002: reducing risks, promoting healthy life*. World Health Organization, Geneva,.

Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs possible? *iied Brief.*, 1–4.

Yamano, T., H. Alderman, and L. Christiaensen, 2005: Child growth, shocks, and food aid in rural Ethiopia. *Am. J. Agric. Econ.*, **87**, 273–288.

Yang, X., and F. Teng, 2016: The air quality co-benefit of coal control strategy in China. *Resour. Conserv. Recycl.*, 1–10, doi:10.1016/j.resconrec.2016.08.011. http://dx.doi.org/10.1016/j.resconrec.2016.08.011.

References for 5.5.1 to come!

Global warming of 1.5 °C

An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

FIGURES

Chapter 1:
Framing and Context

Chapter 2:
Mitigation pathways compatible with 1.5 °C in the context of sustainable development

Chapter 3:
Impacts of 1.5 °C global warming on natural and human systems

Chapter 4:
Strengthening and implementing the global response to the threat of climate change (no figure available yet)

Chapter 5:
Sustainable development, poverty eradication, and reducing inequalities

Chapter 1

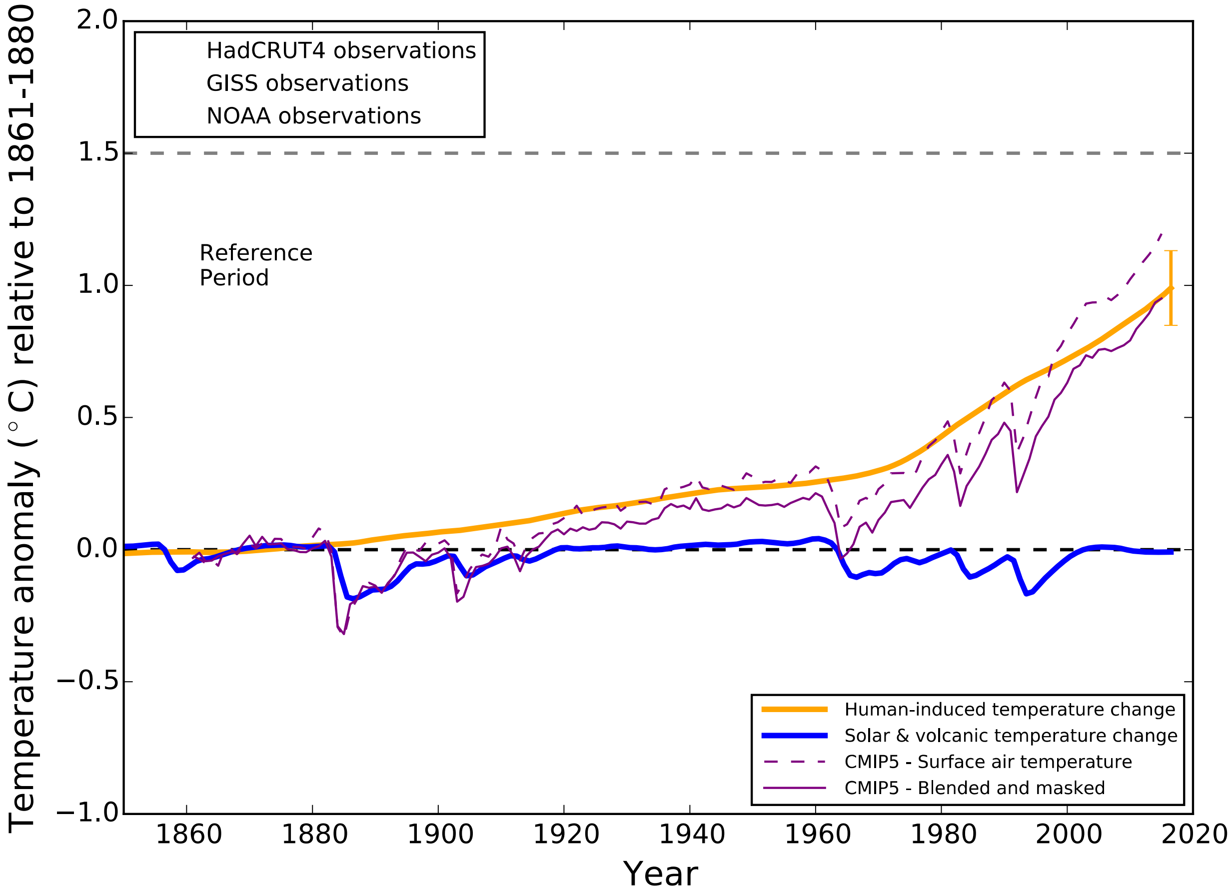


Figure 1.1: Evolution of global warming over the observed period. Warming is expressed as anomalies from the 1861-1880 base period (green shading) for monthly means of the HadCRUT4, NOAA and GISS datasets, which measure a blended mix of near surface air temperature over land and sea surface temperature over oceans. Human-attributable warming (orange) and naturally-forced warming (blue) are calculated using the two time constant response model of Myhre et al. (2013) following Otto et al. (2015). Proportional uncertainty in the final human-attributable warming is set equal to that from Bindoff et al. (2013). The purple lines show the modelled global-mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 ensemble under the Historical and RCP8.5 scenario.

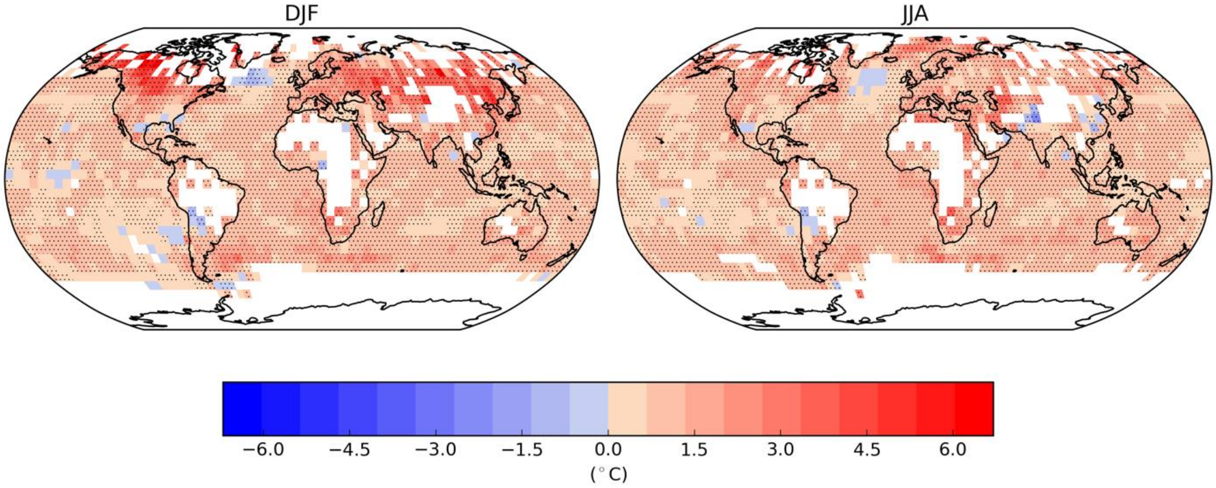


Figure 1.2: Regional human-attributable warming in 2016 relative to 1861-1880 for the average of December, January and Februrary (DJF – left) and for June, July and August (JJA – right). Trends are evaluated by regressing regional changes in the HadCRUT4 dataset onto the human-attributable warming (orange line in Figure 1.1). Data is shown where missing data represents less than 50% of the record. Hatching indicates significance of linear trends at a 10% confidence level assuming uncorrelated Gaussian errors [we will use a more sophisticated significance test in the final version].

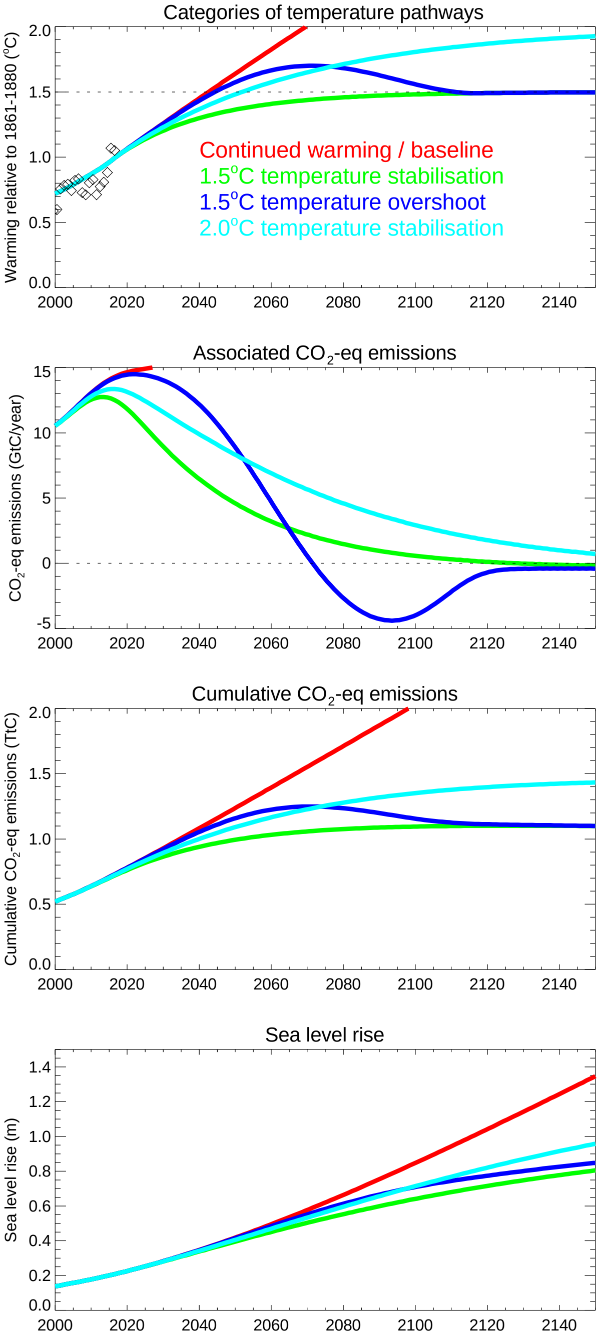


Figure 1.3: Schematic figure showing categories of temperature pathways, with associated emissions (annual and cumulative) and sea-level rise (based on the model of Kopp et al. 2016). Note that CO_2-equivalence is defined here as the rate of CO_2 emission required to give the radiative forcing trajectory that results in the warming shown in the top panel. This is not the same as CO_2-equivalent emissions defined by a conventional use of GWP_{100}.

Figure 1.4: Place holder for a Schematic diagram to illustrate the point, e.g. heat wave risk as an example of an impact that increases more rapidly with warming, while mid-latitude extreme precipitation risk increases approximately linearly, because of the different shapes of the tails of the temperature and precipitation distributions.

Figure 1.5: Placeholder for schematic showing differences in tails of the temperature distribution for a 1.5°C versus 2.0°C world

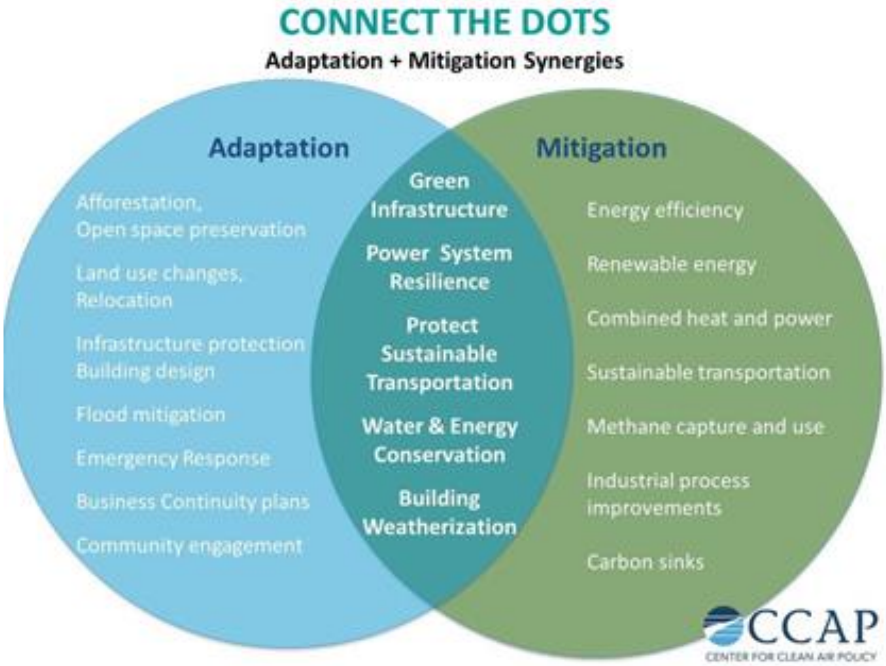


Figure 1.6: Schematic of some adaptation and mitigation options, showing examples of those that serve both to help adaptation and mitigation (figure needs to be redone for this report).

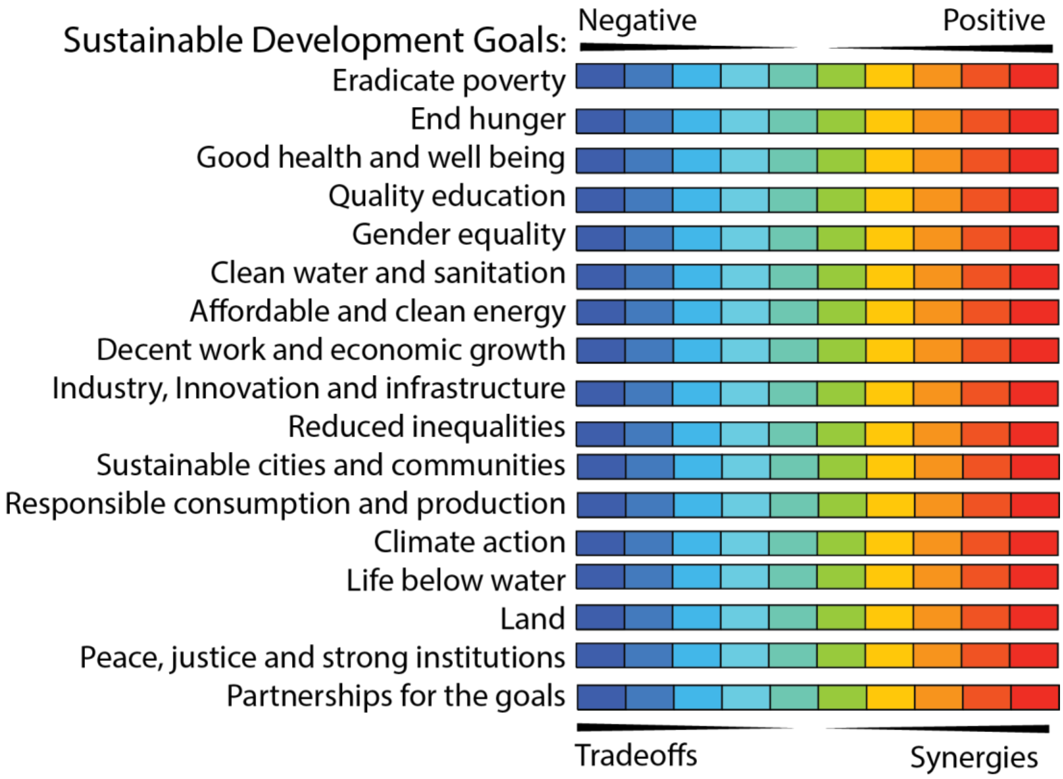


Figure 1.7: A framework for evaluating the impact of different climate response pathways on the multiple dimensions of the Sustainable Development Goals: needs to be edited for inclusion). For each goal, positive or negative impacts for each climate action can be estimated, highlighting the climate response pathways that require tradeoffs versus those that have the most synergies.

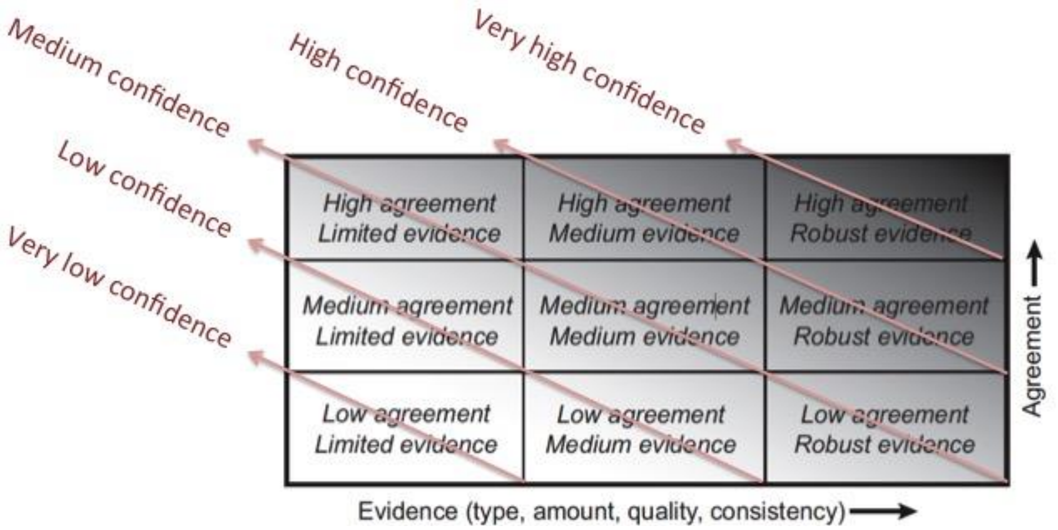
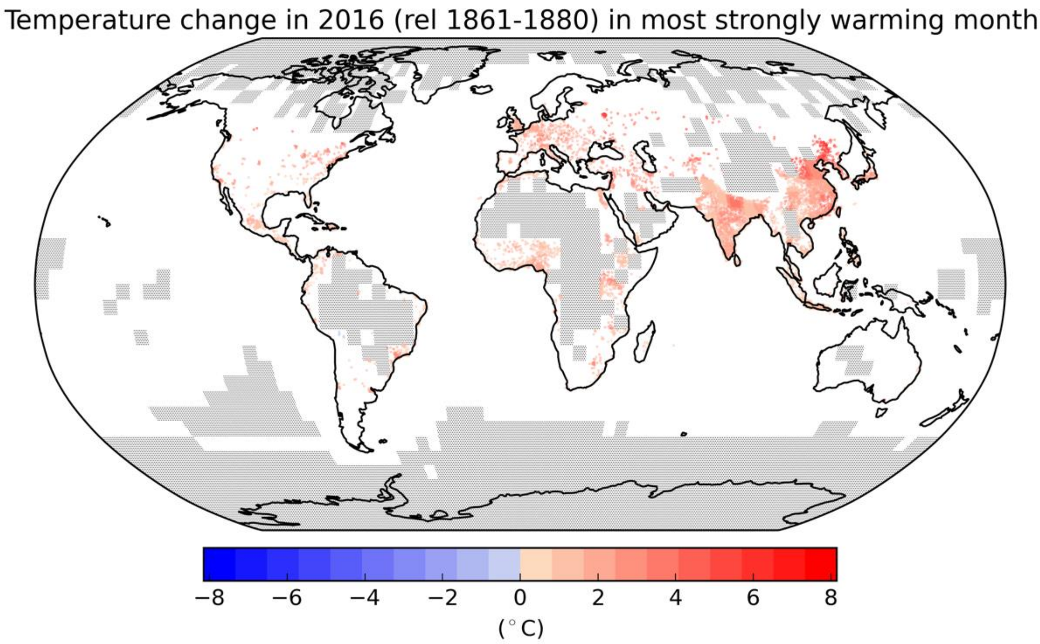
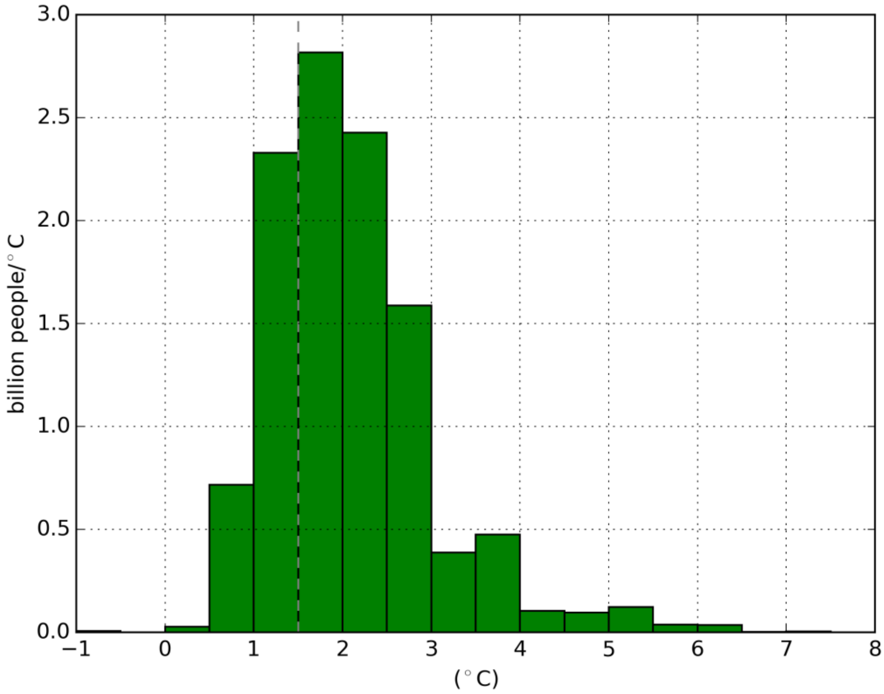


Figure 1.8: The two dimensions of evidence and agreement together determine the level of confidence in a key finding, adapted from Mastrandrea et al. (2011). This figure illustrates how, while there are relatively few ways of supporting a "very high confidence" or "very low confidence" statement, there are multiple ways of supporting a "medium confidence" statement. Note: this figure could be turned on its corner, so the grid is diagonal and the isolines of shading/confidence are horizontal.



Box 1.2, Figure 1: Realized experience of present-day warming. Colors indicate human-induced warming in 2016 (relative to 1861-1880) for the most strongly warming month at any location. The density of dots indicates the population (2015) in any 1°x1° grid box. Warming trends are calculated in an identical way to Figure 1.2. Hatched areas indicate regions where over 50% of the temperature record is missing and warming trends are not calculated.



Box 1.2, Figure 2: Probability density function for the data shown in Figure 1 of this box. Approximately 80% of the global population that live in regions in which local warming trends can be calculated have experienced over 1.5°C of warming in at least 1 month of the year.

Chapter 2

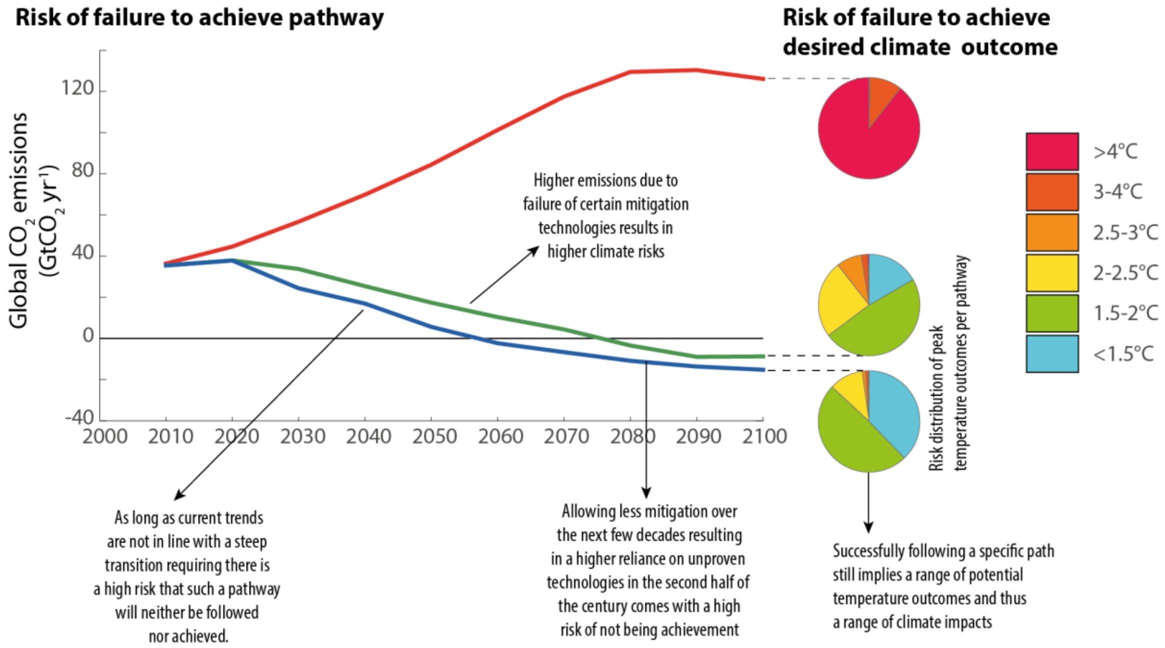


Figure 2.1: Concept of figure illustrating risk of failure to achieve mitigation pathway and risk of failure to achieve desired temperature outcome.

Figure 2.2: Figure suggestion for Carbon budget. Provide a T vs cumulative C plot(s) for the sets of 1.5 and 2 °C pathways that are/will be available, zooming in on the under about 1200 GtC range and compare to AR5. Discuss in detail estimation of range and scientific uncertainty (recognizing the somewhat problematic description of uncertainty in the AR5) of the remaining C budget for T value. We might identify a few illustrative pathways with different characteristics that we would carry through the following sections.

Figure 2.3: idea: Uncertainties and constraints to the budget: something like Figure 3 from Knutti and Hegerl 2008 but showing unconstrained budget of CO_2 at the top and squeezing more and more when other GHGs and uncertainties are added (maybe two figs – one showing squeezing and one showing uncertainty. Separate out (TCRE, Pathway, non-CO_2 forcing?). Maybe another set of figs for remaining budget) maybe a bit like the following fig from Rogelj et al (2014) but include more uncertainties, not just ECS. [Link with Section 2.2]

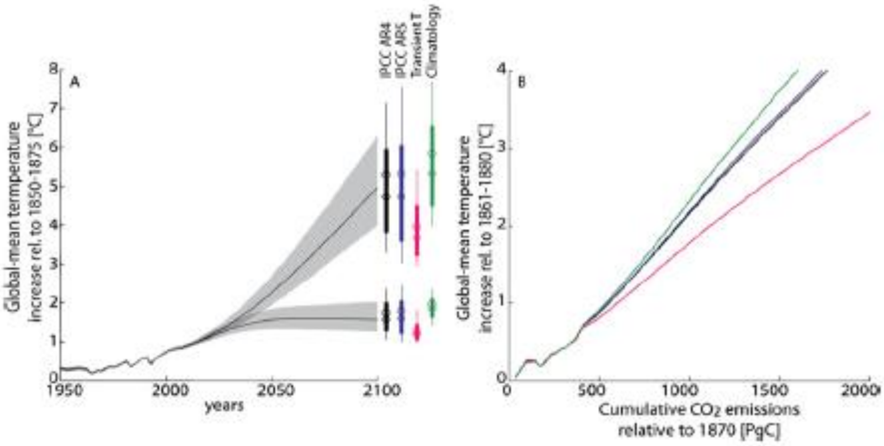


Figure 2.4: **idea:** Bar chart with $\Delta CO2/\Delta T$ effect and potential feedbacks on $\Delta CO2$ derived from AR5 table (and ΔT if know/quantified feedback)

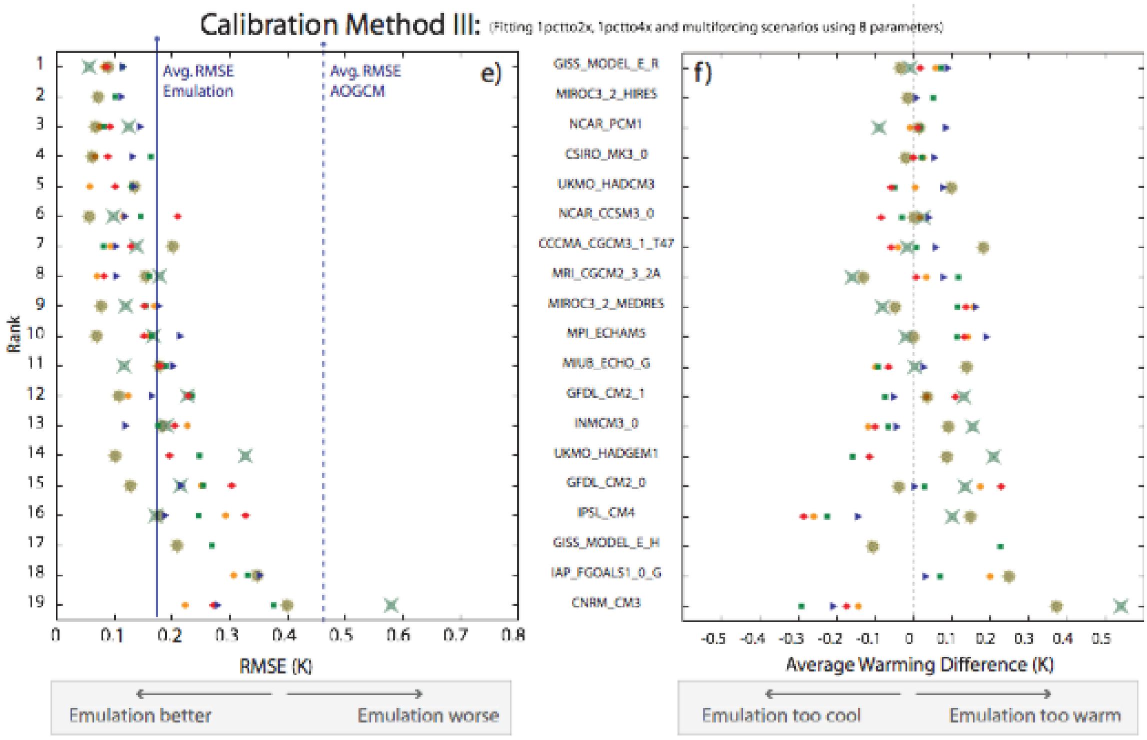


Figure 2.5: Calibration of MAGICC against CMIP3 AOGCM (from (Meinshausen et al. 2011) on global mean temperature using a subset of height parameters.

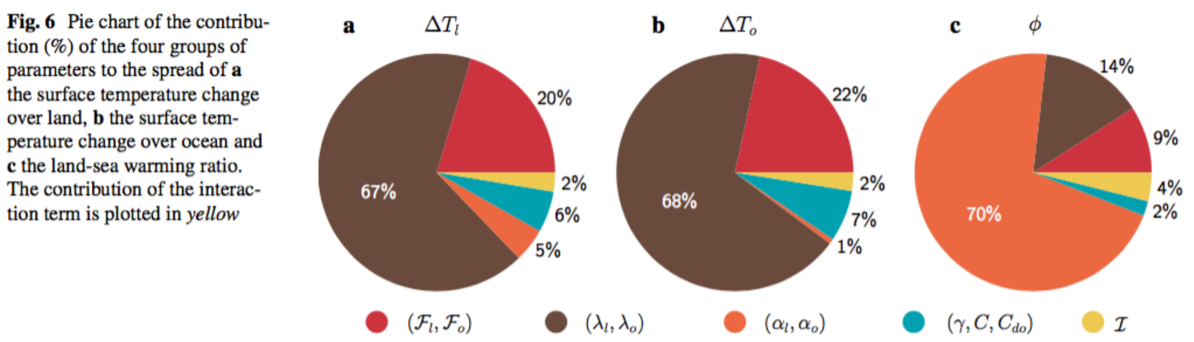


Figure 2.6: from (Geoffroy et al. 2015) using another climate emulator: illustration of trade-offs between calibration parameters to capture AOGCM (a) global mean temperature, (b) average sea surface temperature and (c) land-sea warming ratio.

Figure 2.7: **idea:** it could be nice to update figure of carbon budget and temperatures outcomes with available results of rcp1.9 + rcp2.6 and SRES …

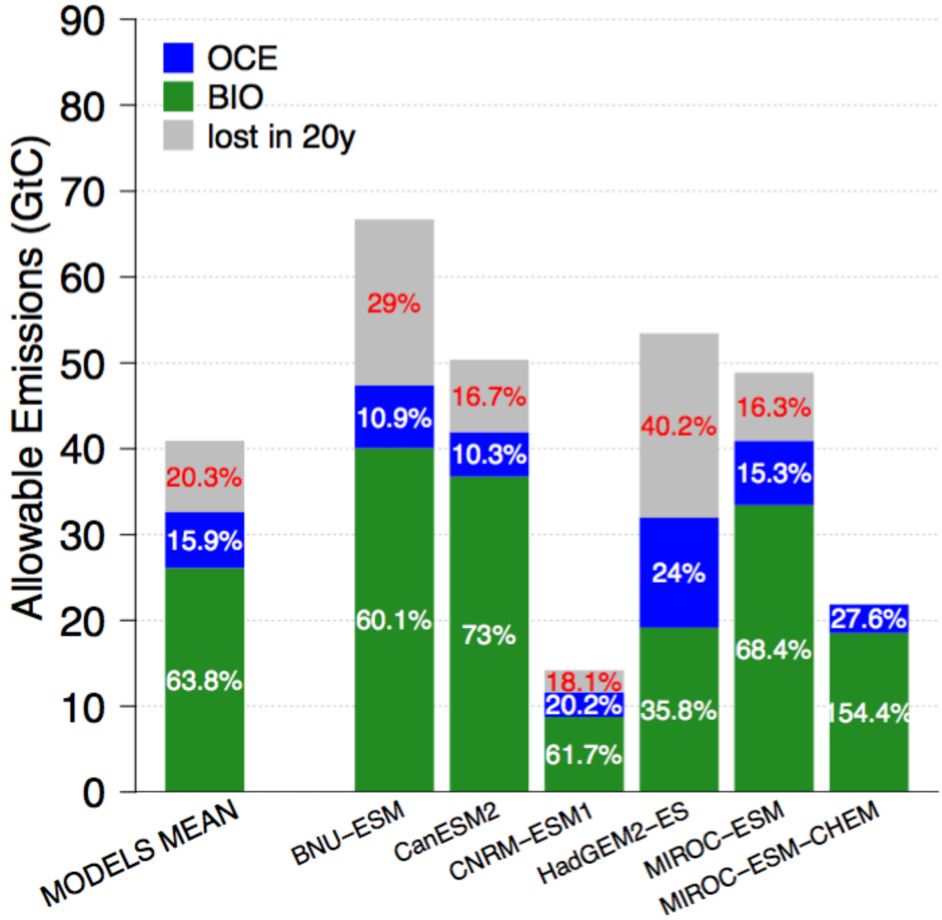


Figure 2.8: Allowable carbon emissions induced by SRM in stratospheric injection of 4 TgSO2 per year from jan-2020 to dec-2069 (G4 GeoMIP). Total storage is partitioned into land biosphere storage (green) and ocean storage (blue). Grey bars indicate the amount of carbon released to the atmosphere 20 years after the cessation of the SRM (Plazzotta et al. in prep)

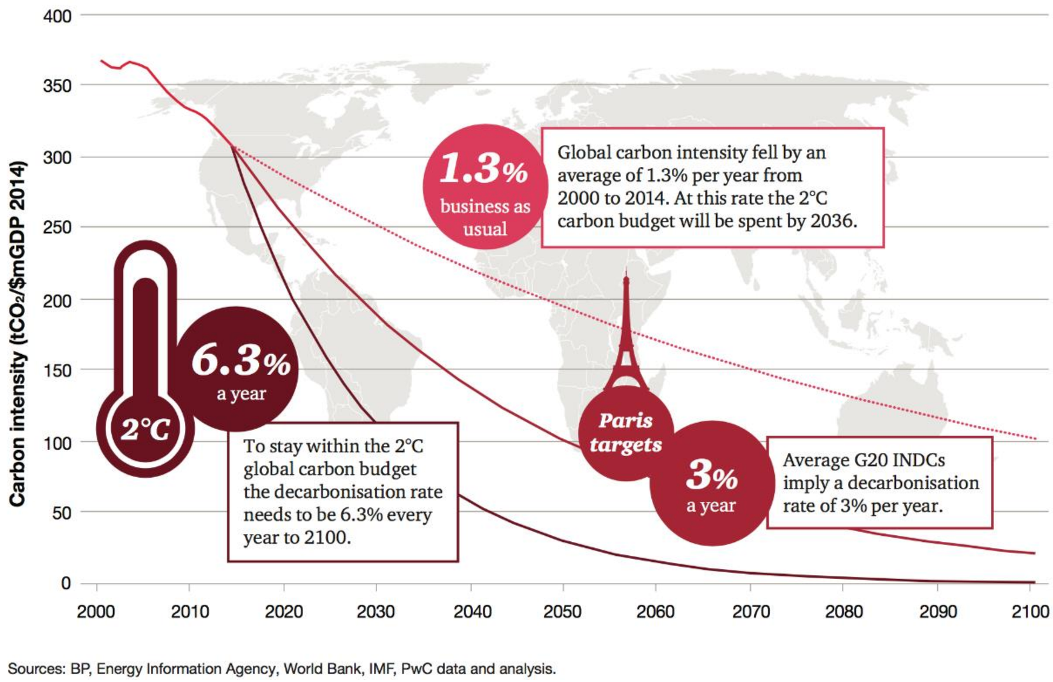


Figure 2.9: **idea/concept:** carbon intensity pathways for BAU, NDC targets and 1.5°C (like the one below for 2°C) as part of a larger mosaic figure. Issue to be resolved for such a figure, decarbonisation rates as computed in this figure become infinite as emissions become negative.

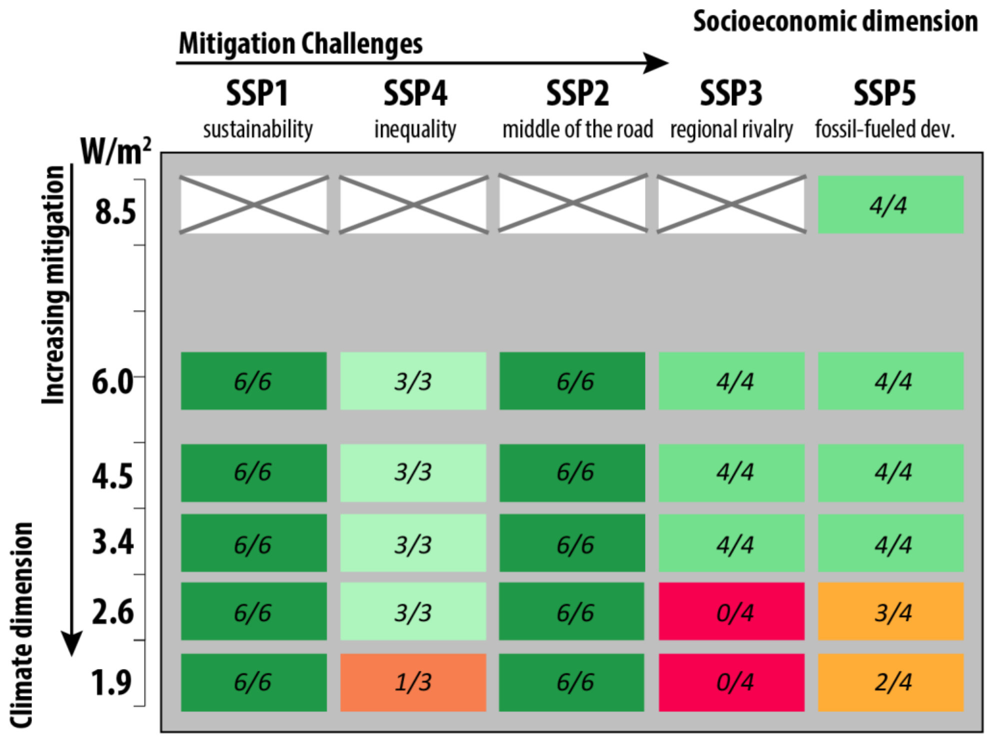


Figure 2.10: a figure idea and concepts: Overview of successful scenario runs in SSP-RCP matrix framework. Values in each box represent the number of successful scenario runs over the number of participating modelling frameworks. From (Rogelj et al., in review), but can also be based on the IPCC SR1.5 scenario database.

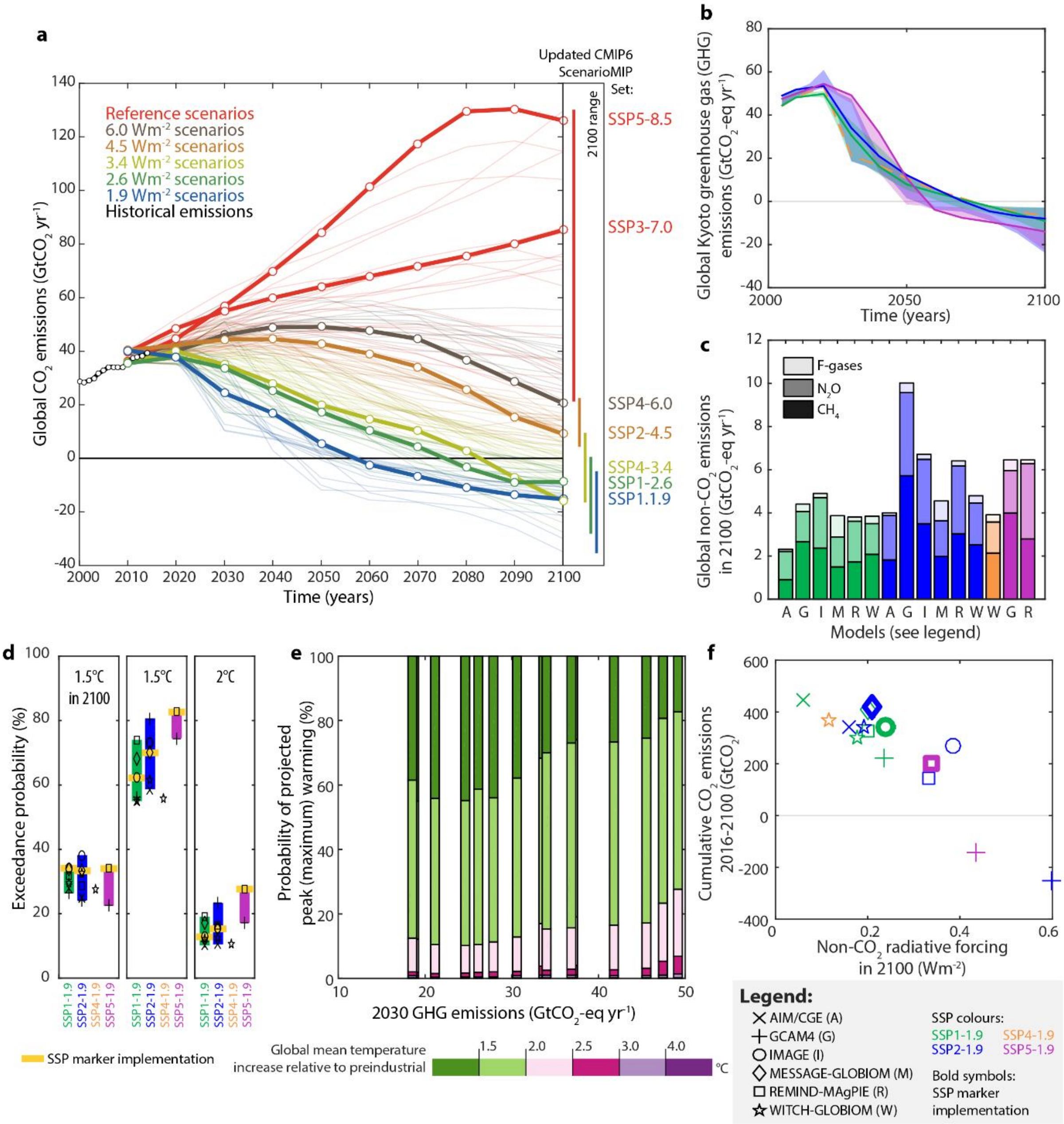


Figure 2.10b figure idea and concepts: Emission and temperature characteristics of 1.9 Wm^{-2} scenarios under varying SSPs. a, Global CO_2 emissions of current SSP scenarios with the subset selected for CMIP6 ScenarioMIP highlighted. Historical emission from ref. 34. All other panels show 1.9 Wm^{-2} scenario data only; **b**, Global Kyoto GHG emissions. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers; **c**, Non-CO_2 GHGs per scenario in 2100; **d**, Exceedance probability of various temperature limits for 1.9 Wm^{-2} scenarios with bars showing the full range over all available scenarios per SSP. Except for the first sub-panel all other panels give the exceedance probability over the entire 21st century; **e**, Probability of peak warming versus 2030 GHG emissions in 1.9 Wm^{-2} scenarios; **f**, Dependence of cumulative CO_2 emissions on non-CO_2 RF in 2100. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

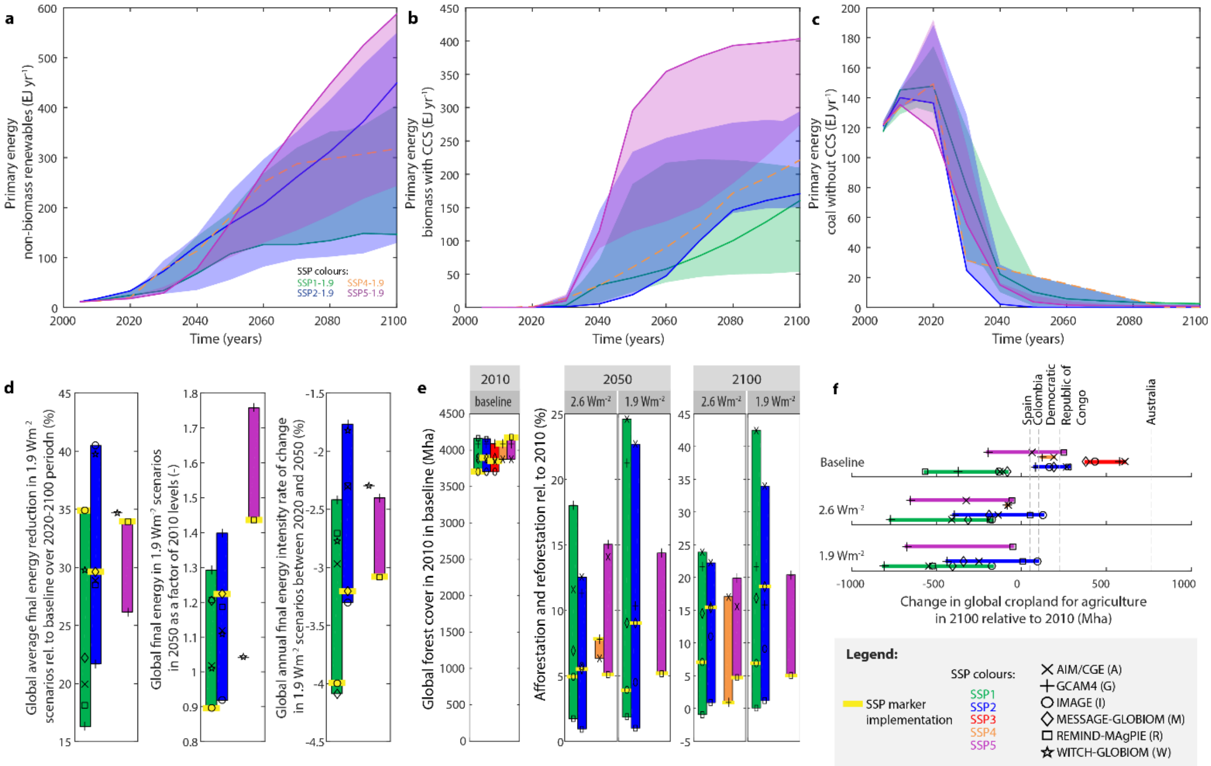


Figure 2.10c **figure idea and concepts: Overview of key decarbonisation characteristics in 1.9 Wm^{-2} scenarios. a**, Primary energy from non-biomass renewables (wind, solar, hydro, and geothermal energy); **b**, Primary energy from biomass with CCS (BECCS); **c**, Primary energy from coal without CCS. Shaded areas in panels **a-c** show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers; **d**, Illustration of global final energy demand in 1.9 Wm^{-2} scenarios showing the average reduction from baseline over the 2020-2100 period, the change in 2050 compared to 2010 levels, and the annual rate of final energy intensity change, respectively; **e**, Global forest cover, and change relative to 2010 due to afforestation and reforestation in 2.6 and 1.9 Wm^{-2} scenarios; **f**, Change in global cropland for agriculture in 2100 relative to 2010 in 'Baseline' scenarios in absence of climate change mitigation, as well as in 2.6 and 1.9 Wm^{-2} scenarios. Results are grouped per SSP (coloured lines with black symbols). From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

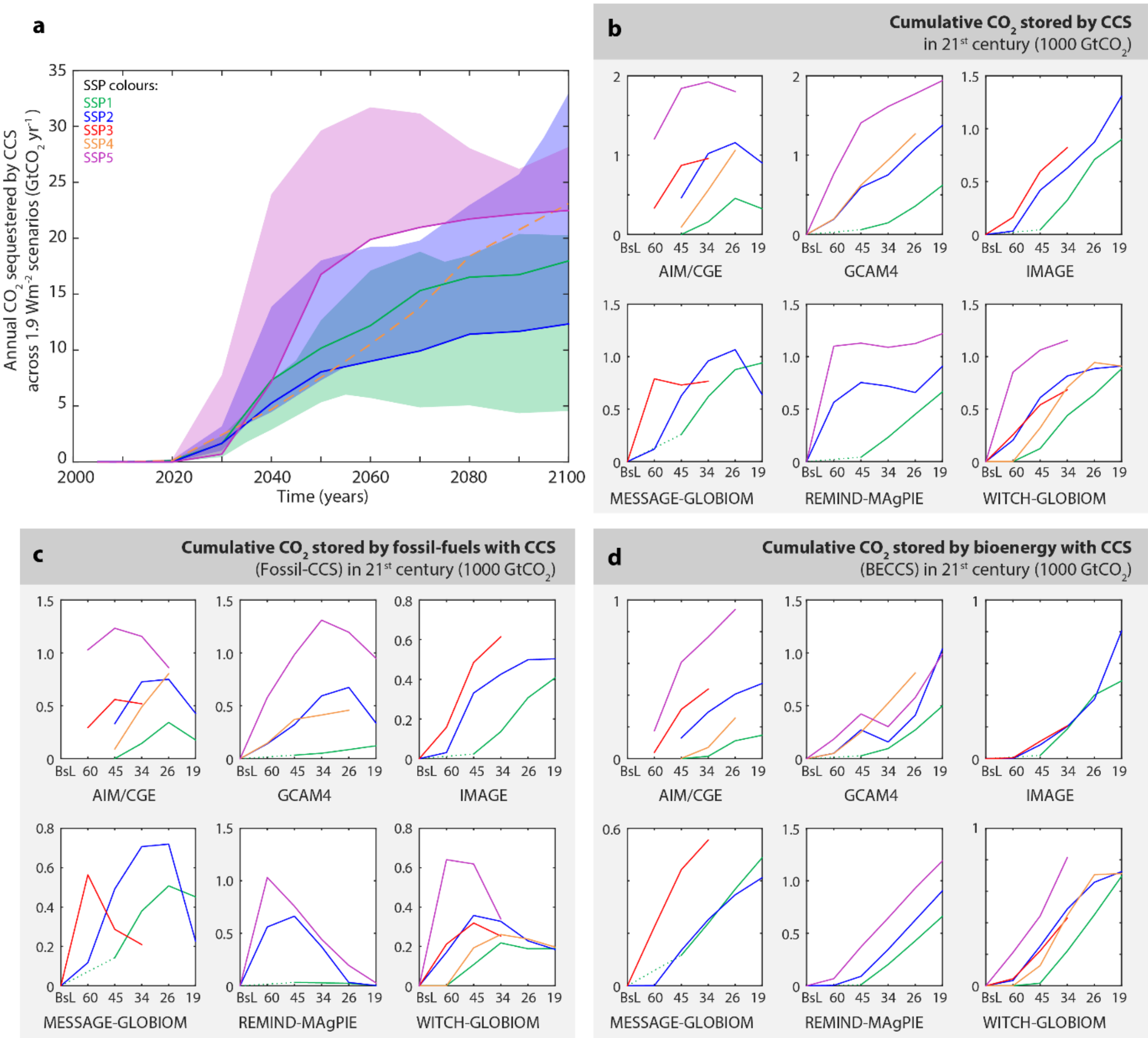


Figure 2.10d **figure idea and concepts: BECCS, Fossil-CCS and CCS across SSPs and across climate targets. a**, Annual amount of CO_2 stored by CCS in 1.9 Wm^{-2} scenarios. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers; **b**, Variation per modelling framework and per SSP of cumulative CO_2 stored by CCS during the 21st century when moving from a world in absence of climate policy (baseline, BsL) to increasingly more stringent climate targets (6.0, 4.5, 3.4, 2.6, and 1.9 Wm^{-2}); **c**,**d**, As panel **b** but for Fossil-CCS and BECCS, respectively. Note that axis limits vary across models. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

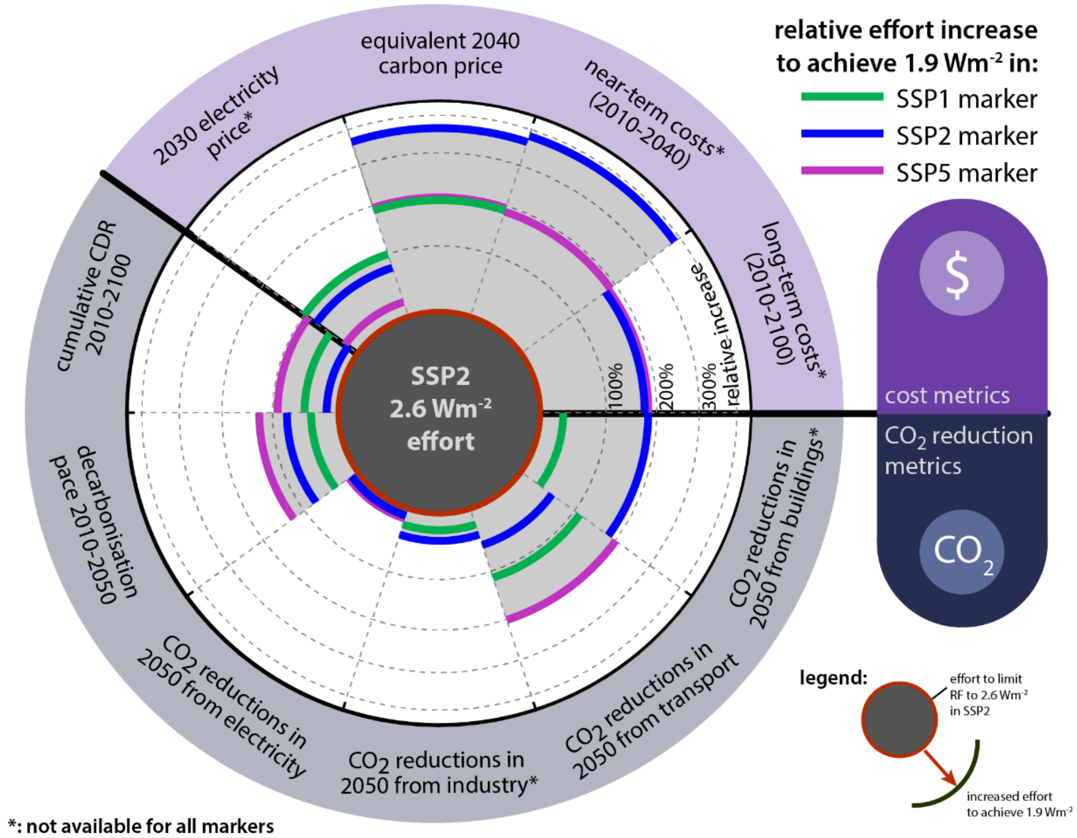


Figure 2.10e figure idea and concepts: Differential mitigation characteristics when moving from a 2.6 Wm^{-2} to a 1.9 Wm^{-2} scenario. Updated from Rogelj et al (NCC, 2015). Indicators are: long-term mitigation costs (2010–2100 aggregate consumption losses relative to baseline discounted at 5%); short-term mitigation costs (2010–2040 aggregate discounted at 5%); 2040 global emission-weighted equivalent carbon price level; electricity price in 2030; cumulative CDR between 2010 and 2100 including BECCS and CO_2 removal by land use and land-use change; decarbonisation pace (average linear 2010–2050 rate of reductions in energy-related CO_2 emissions); reductions in CO_2 emissions from electricity from baseline in 2050; reductions in CO_2 emissions from industry from baseline in 2050; reductions in CO_2 emission from transport from baseline in 2050; and reductions in CO_2 emissions from buildings from baseline in 2050. Data is shown for the marker implementations of SSP1, SSP2, and SSP5 but can also be shown as ranges per SSP. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

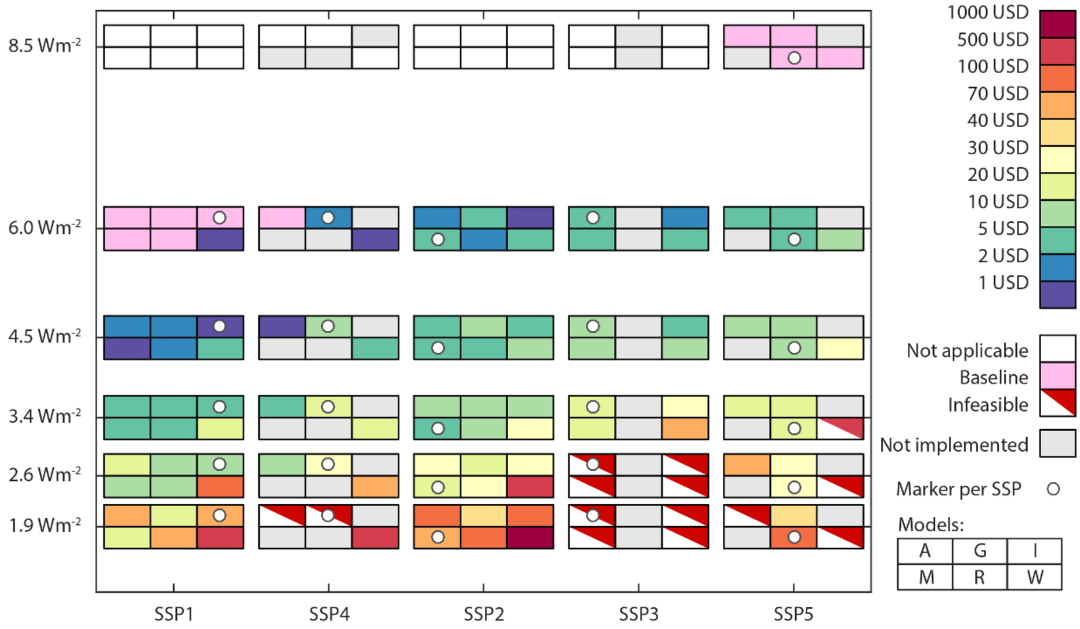


Figure 2.10f **figure idea and concepts: Variation of carbon prices over SSP and RF target space.** Shown values are average global average carbon prices over the 2020-2100 period discounted to 2010 with a 5% discount rate. Mitigation challenges are assumed to increase from left to right across the SSPs (i.e., SSP1, SSP4, SSP2, SSP3, SSP3). Each box represents one model-SSP-RF target combination. A: AIM/CGE, G: GCAM4, I: IMAGE, M: MESSAGE-GLOBIOM, R: REMIND-MAgPIE, W: WITCH-GLOBIOM. All scenarios with a carbon price greater than 0 (i.e. all but the baselines) have been designed to reach one of the RF targets on the vertical axis. Models for which no pink baseline data is indicated have baselines which result in an end-of-century RF between 6.0 and 8.5 Wm^{-2}. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

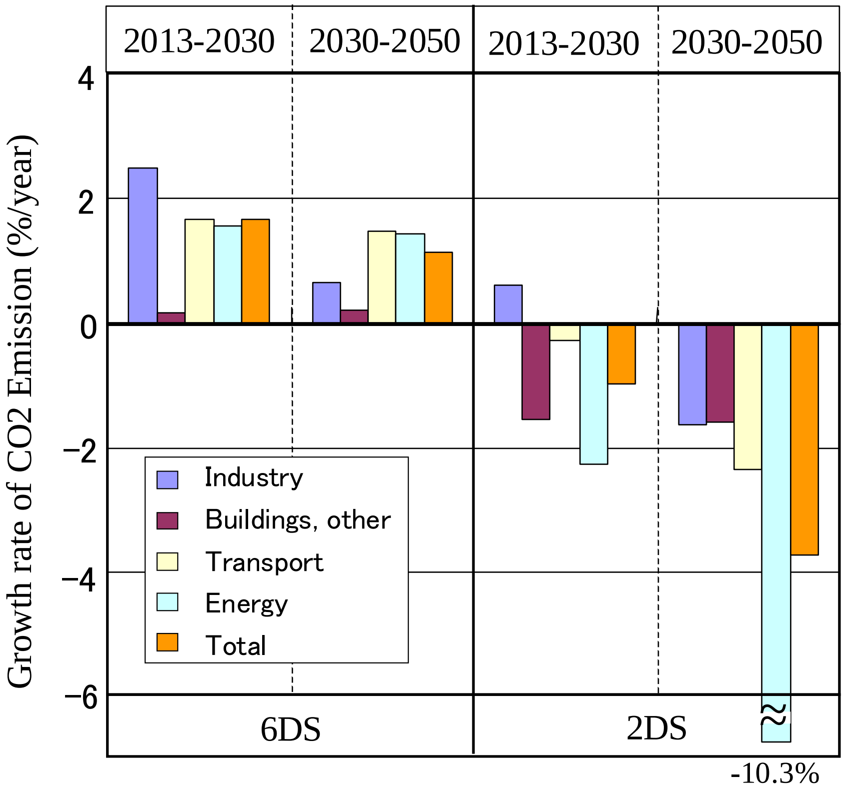


Figure 2.10g figure idea and concepts: rate of CO_2 emission change for 2°C scenario. From IEA. The same figure could be made for 1.5°C scenarios and the difference between the scenarios can be discussed.

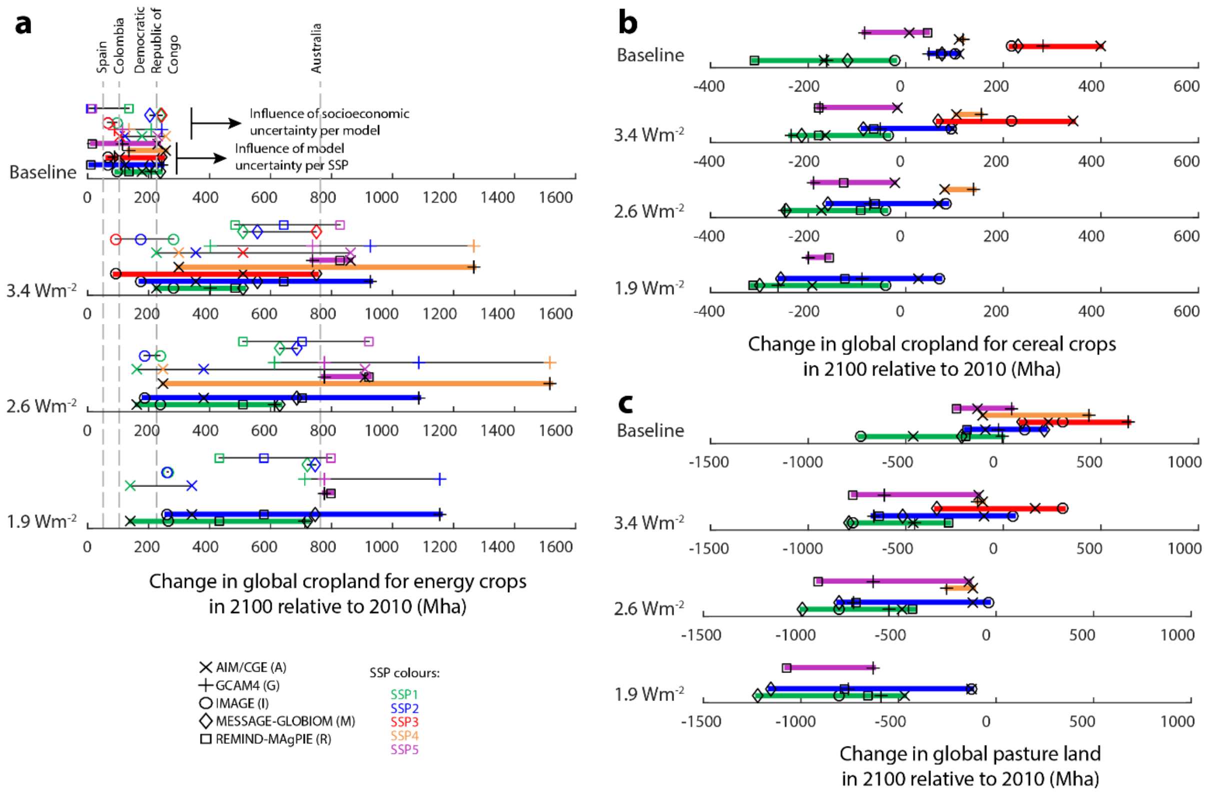


Figure 2.10h **figure idea and concepts: Variation of change of land area dedicated to specific uses in 2100 relative to 2010.** For each modelling framework and each SSP the change in global cropland for energy crops (panel **a**), cereal production (panel **b**) and pasture (panel **c**) is illustrated when moving from a world in absence of climate policy (Baseline) to more stringent climate targets (3.4, 2.6, and 1.9 Wm^{-2} in 2100). Both the influence of socioeconomic uncertainty as captured by the SSPs per model (black lines with coloured symbols) and the influence of model uncertainty per SSPs (coloured lines with black symbols) is shown. Data behind thin black lines and thick coloured lines in panel **a** is identical, but grouped differently. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

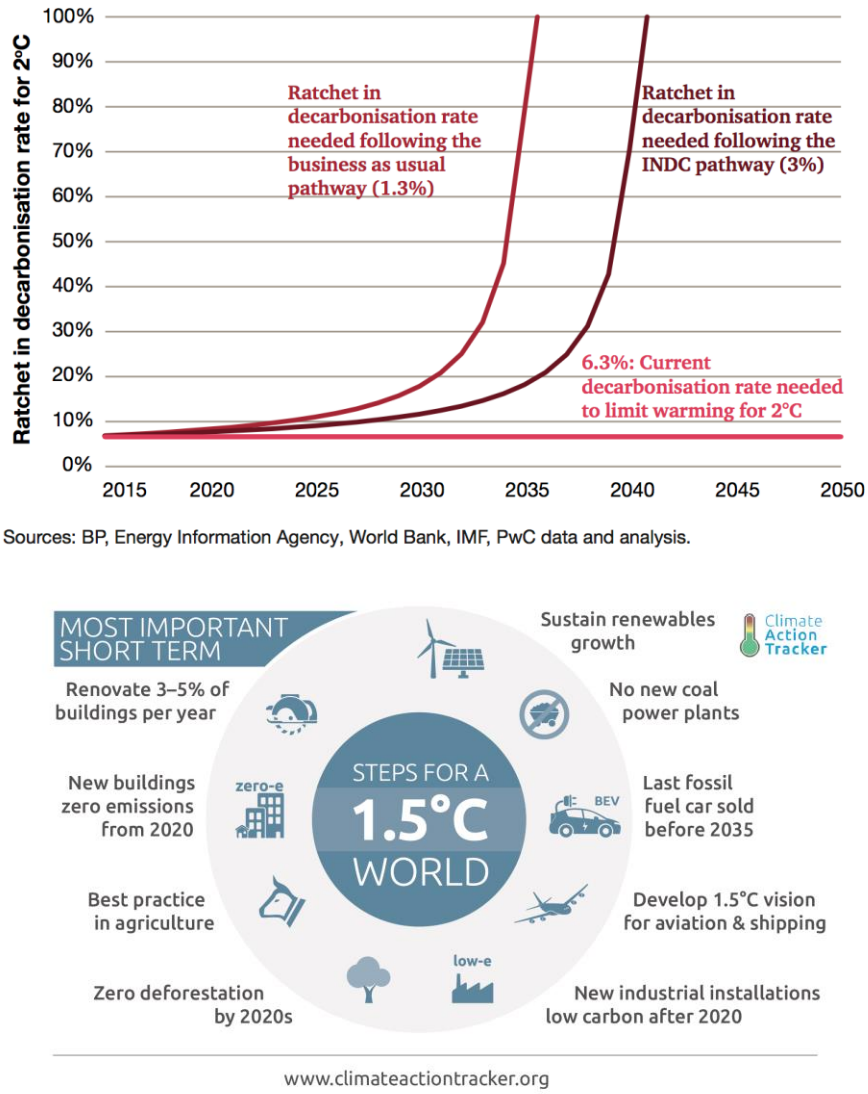


Figure 2.11: (a) Figure idea/concepts: Concepts for summary figures showing the assessment outcomes.

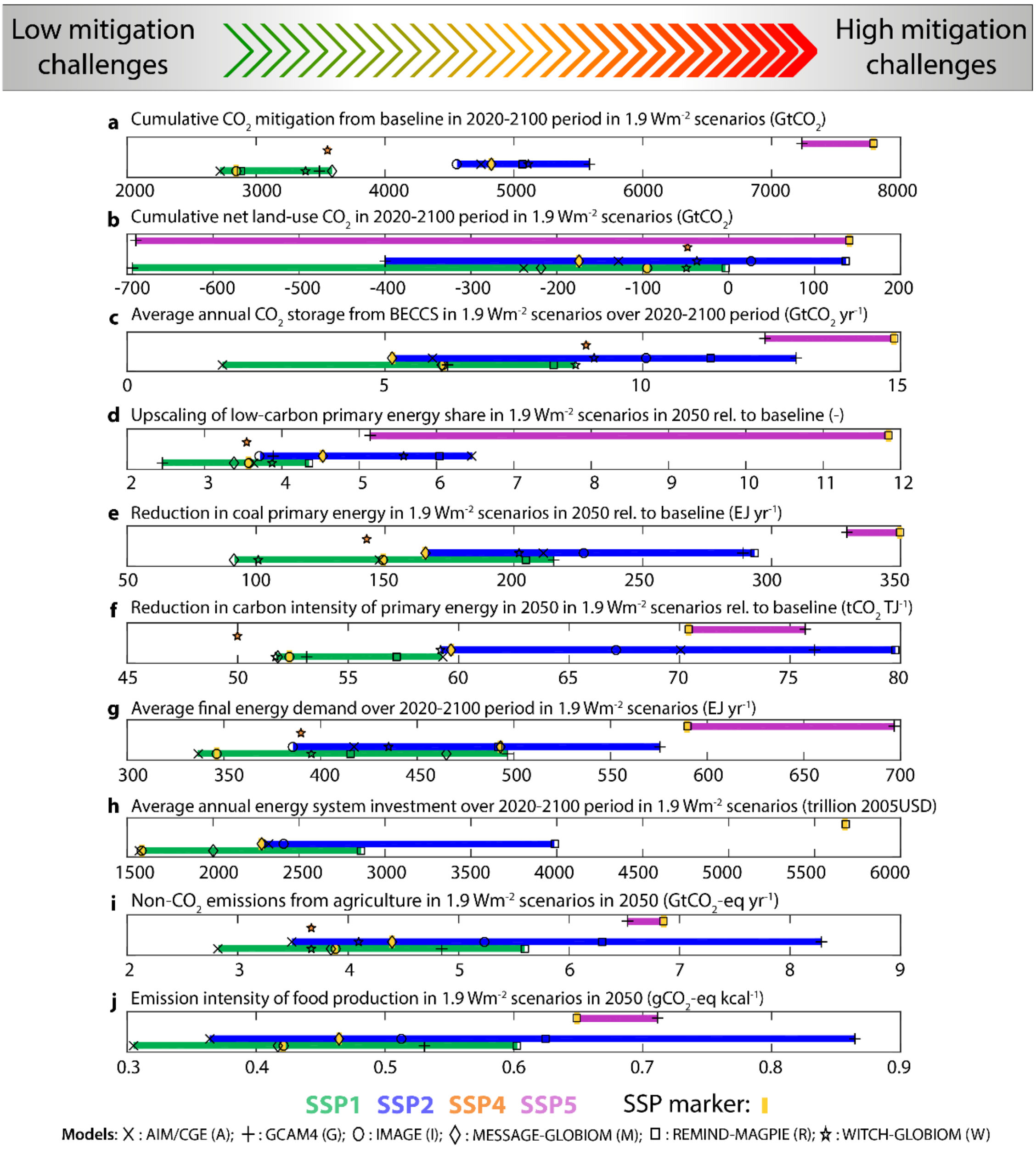


Figure 2.11b – Figure ideas and concepts: Variation in mitigation challenges for limiting end-of-century RF to 1.9 Wm^{-2} across the SSPs. a-j, Panels show various dimensions of climate change mitigation challenges. Ranges show the minimum-maximum range across models per SSP. Symbols show single models. The yellow stripe indicates the marker implementation for each respective SSP. As not all modelling frameworks provide all necessary indicators, some panels show less models. No model was successful in producing a 1.9 Wm^{-2} scenario for SSP3. From (Rogelj et al., in review), but will be based on the IPCC SR1.5 scenario database.

Figure 2.12: Time of warming peak vs. time of carbon neutrality across 1.5°C and well below 2°C scenarios.

Figure 2.13: Residual non CO2-emissions / forcing. (a) Emissions of N2O (stacked bar by source as an average over scenarios / for selected scenarios within 1.5°C and well below 2°C scenario classes) in 2050 and 2100 (compared to 2011); (b) Forcing from F-gases and ODS (stacked bar by species as an average over scenarios / for selected scenarios within 1.5°C and well below 2°C scenario classes) in 2050 and 2100 (compared to 2011); (c) Forcing from short-lived climate forcers and other aerosol and ozone precursors (stacked bar by species as an average over scenarios / for selected scenarios within the 1.5°C and well below 2°C scenario classes) in 2050 and 2100 (compared to 2011); (d) Re-calculation of residual forcing from non-CO_2 climate forcing into temperature penalty (DT~ECS*RF/RF(2xCO_2)) or CO_2 emission budget penalty (DT/TCRE), if possible.

Figure 2.14: Carbon Dioxide Removal CDR (a) Carbon and long-lived GHG Budgets 2016-2100 split into several contributions (stacked bar as an average / selected scenario per scenario class) across 1.5°C and well below 2°C scenario categories. Contributions include CO2 net budget (A) plus compensation from peak budget (B), possibly split into CDR contributions until and after carbon / emissions neutrality; (b) CDR 2016-2100 (in GtCO2) split into CDR measures (stacked bar as an average / selected scenario per scenario class and models with same CDR portfolio) across 1.5°C and well below 2°C scenario categories and separated along CDR availability (only BECCS, BECCS & afforestation, BECCS & DAC, more than two); (c) Land requirements (in 2100 compared to 2010) for afforestation and BECCS as a function of CDR from these two options separated along CDR availability (only BECCS, BECCS & afforestation, BECCS & DAC, more than two); (d) CO2 sequestered in geological formations (2016-2100) from BECCS, DAC and fossil fuel CCS separated along CDR availability (only BECCS, BECCS & DAC).

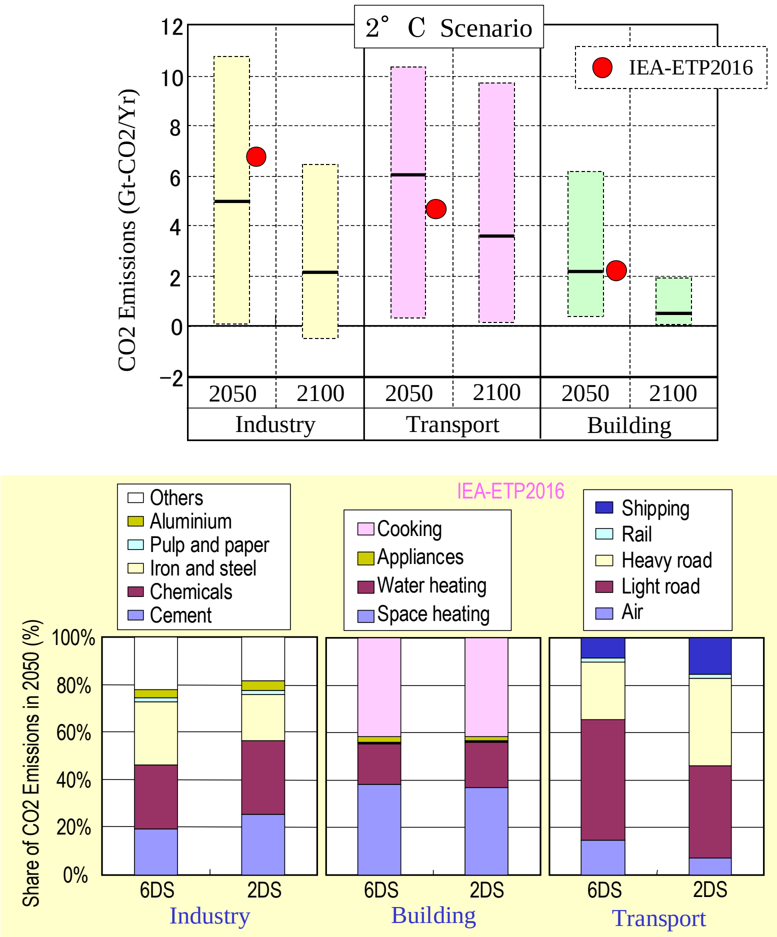


Figure 2.15: Residual emissions and deep mitigation [based on suggestions from earlier reports and IEA]Sectorial CO2 and non-CO2 emissions in 2050 and 2100; (b) Electrification in sectors in 2050 and 2100; (c) Amount and composition of residual liquids / gases / solids use in sectors in 2050 and 2100; (d) Sectorial shares.

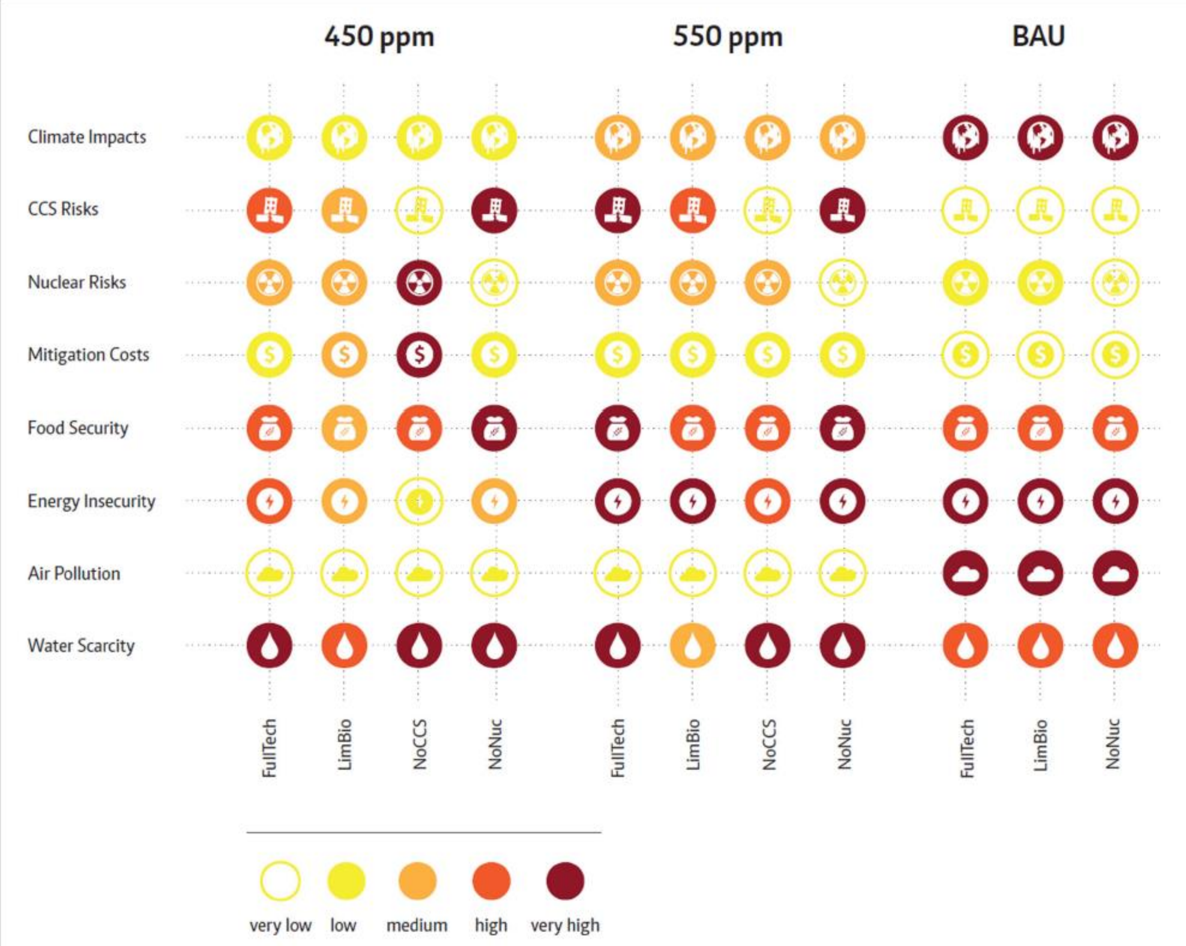


Figure 1. The option space for climate policy is determined by implications for sustainable development in multiple dimensions. Policy formulation will depend on an assessment of trade-offs and synergies between these dimensions.

Figure 2.16: Figure concepts: Non-climate implications of climate policy. Source: (Jakob and Steckel, 2016).

Chapter 3

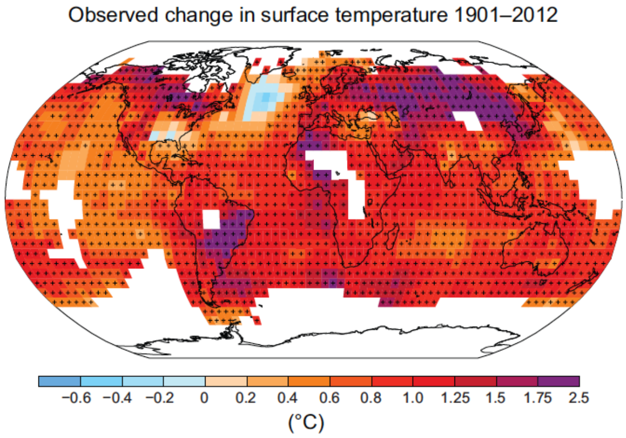


Figure 3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. From Stocker et al. (2013)

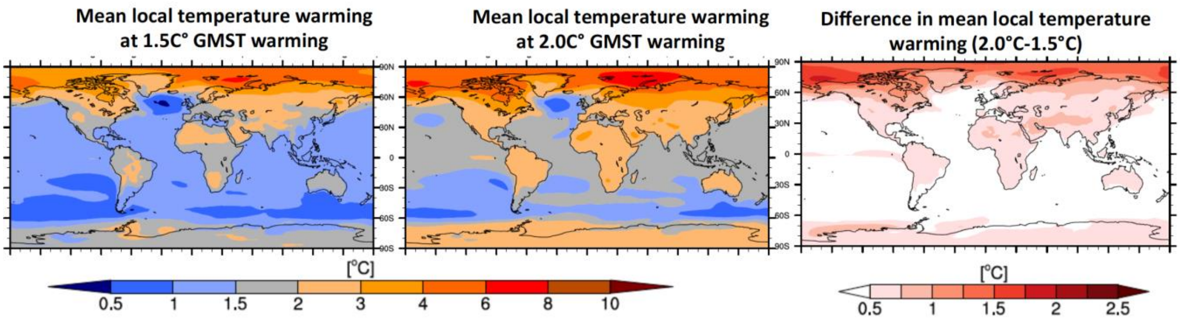


Figure 3.2: Projected local mean temperature warming at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016)). Note that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see Supplementary Figure S3.3.3).

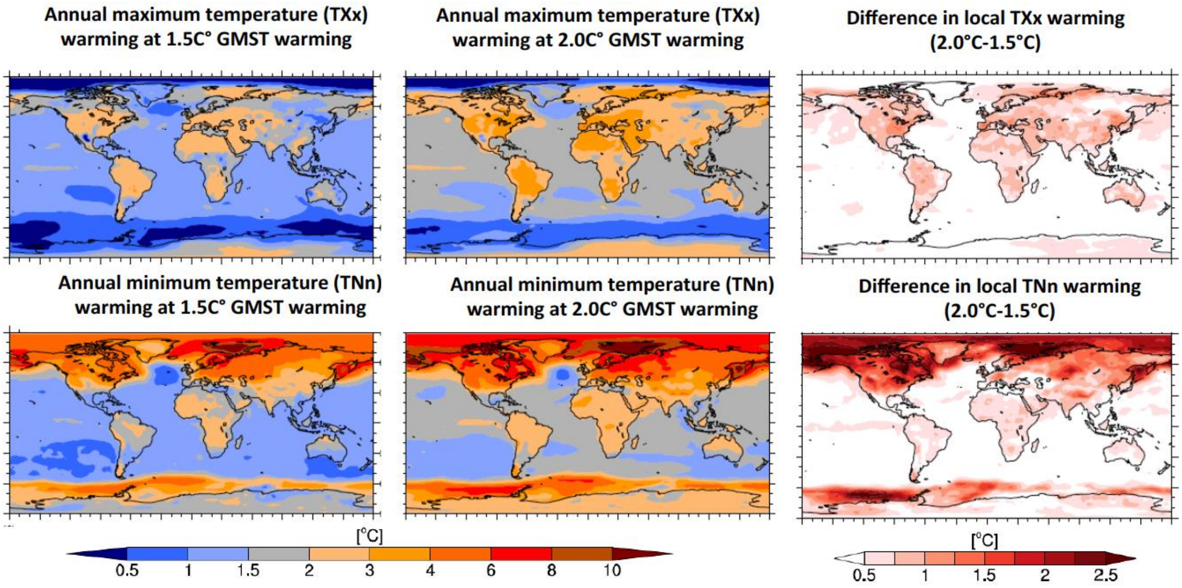


Figure 3.3: Projected local warming of extreme temperatures (top: Annual maximum daytime temperature, TXx; bottom: Annual minimum nighttime temperature, TNn) warming at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016). Note that the warming at 1.5°C GMST warming is similar for RCP2.6 simulations (see Supplementary Figure S3.3.4).

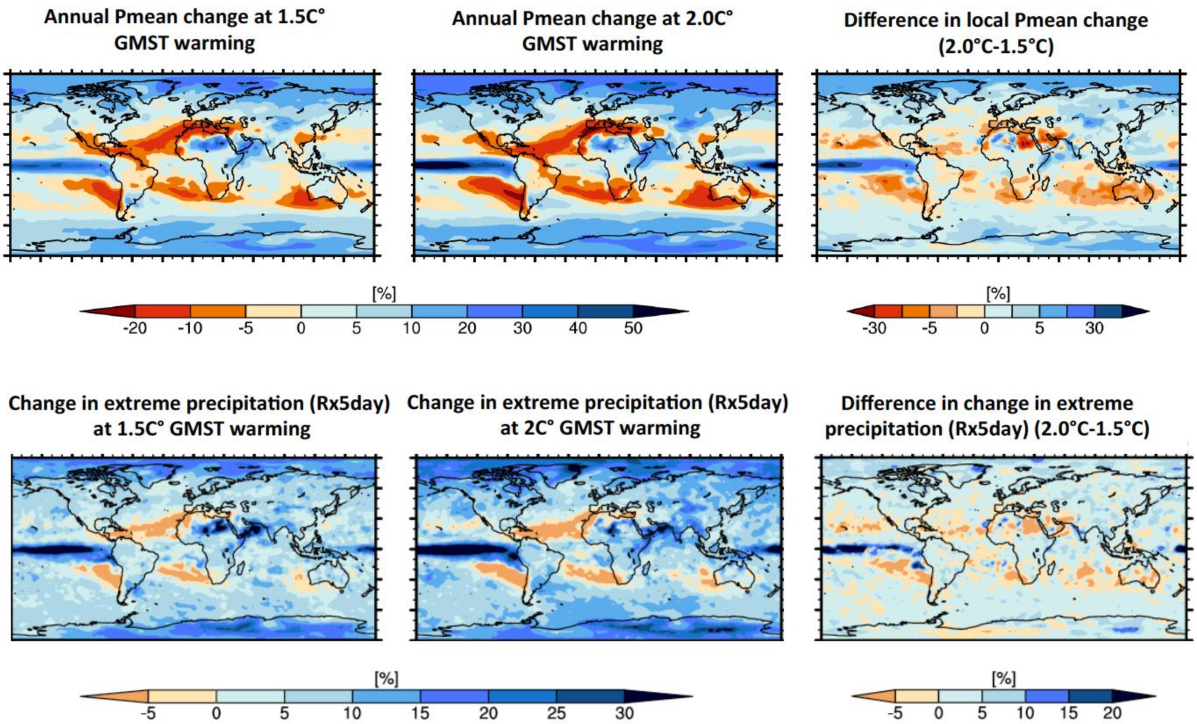


Figure 3.4: Projected changes of mean (top) and extreme (5-day maximum precipitation) precipitation at 1.5°C global warming (left), 2.0°C global warming (middle), and difference (right). Assessed from transient response over 20-year time period at given warming, based on RCP8.5 CMIP5 model simulations (adapted from Seneviratne et al. (2016). Note that the response at 1.5°C GMST warming is similar for the RCP2.6 simulations (see Supplementary Figure S3.3.5).

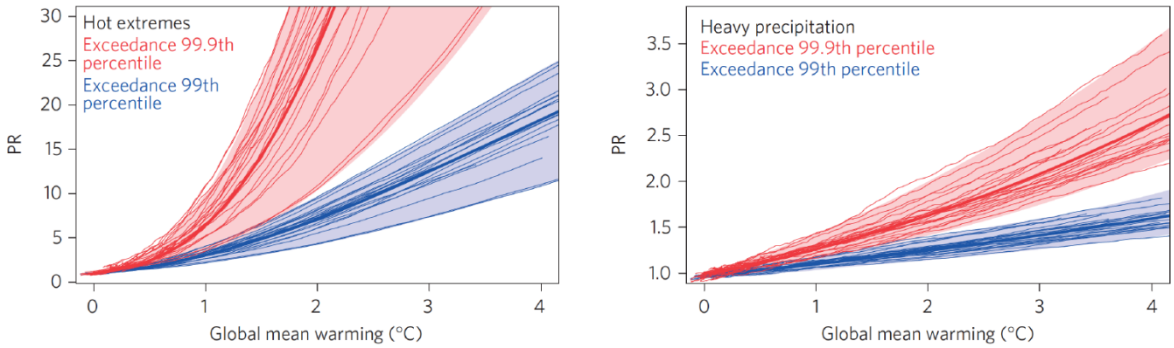


Figure 3.5: Probability ratio of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature (left) and precipitation (right) at a given warming level relative to pre-industrial conditions averaged across land [from Fischer and Knutti (2015)].

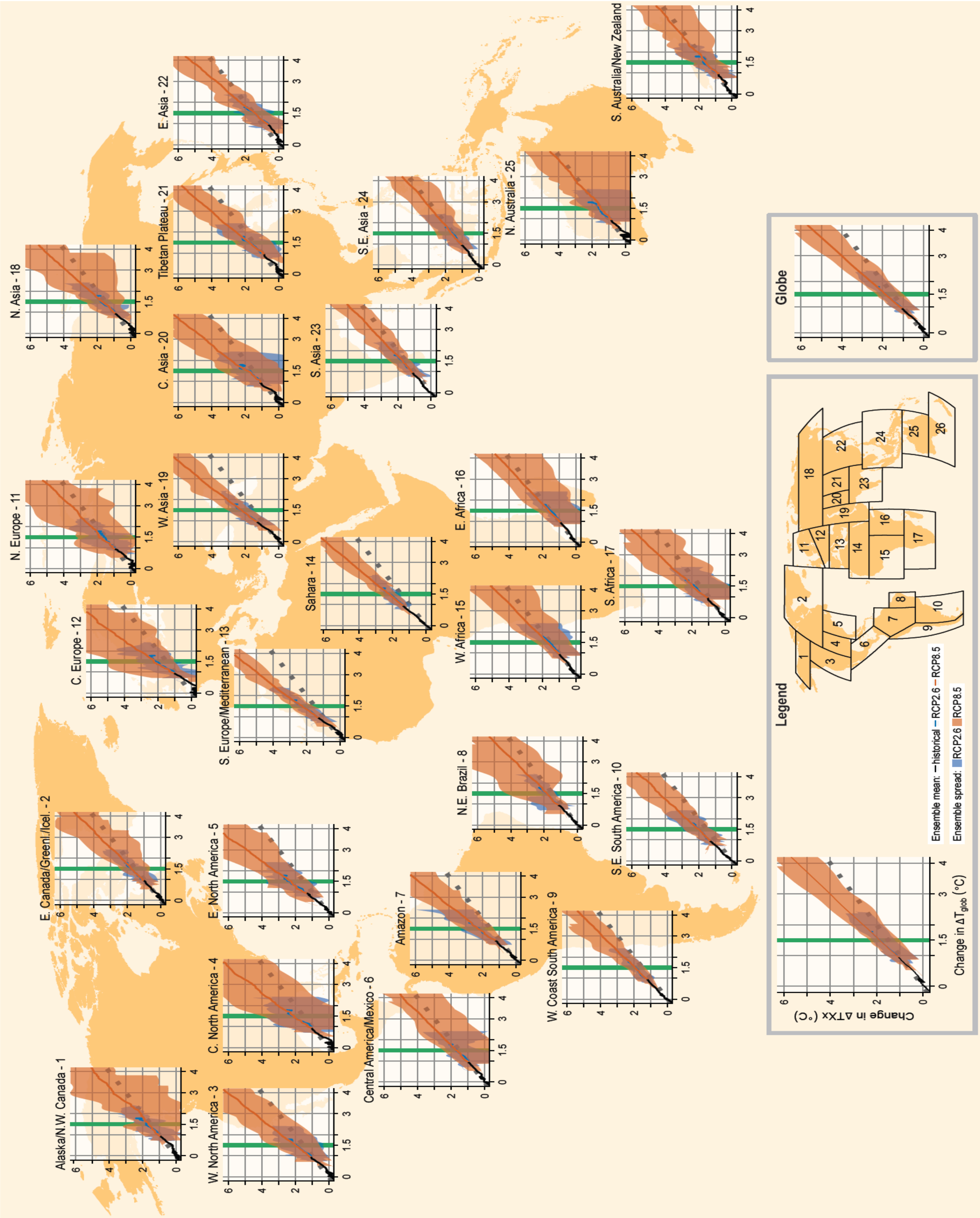


Figure 3.6: Projected changes in annual maximum daytime temperature (TXx9 as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger and et al).

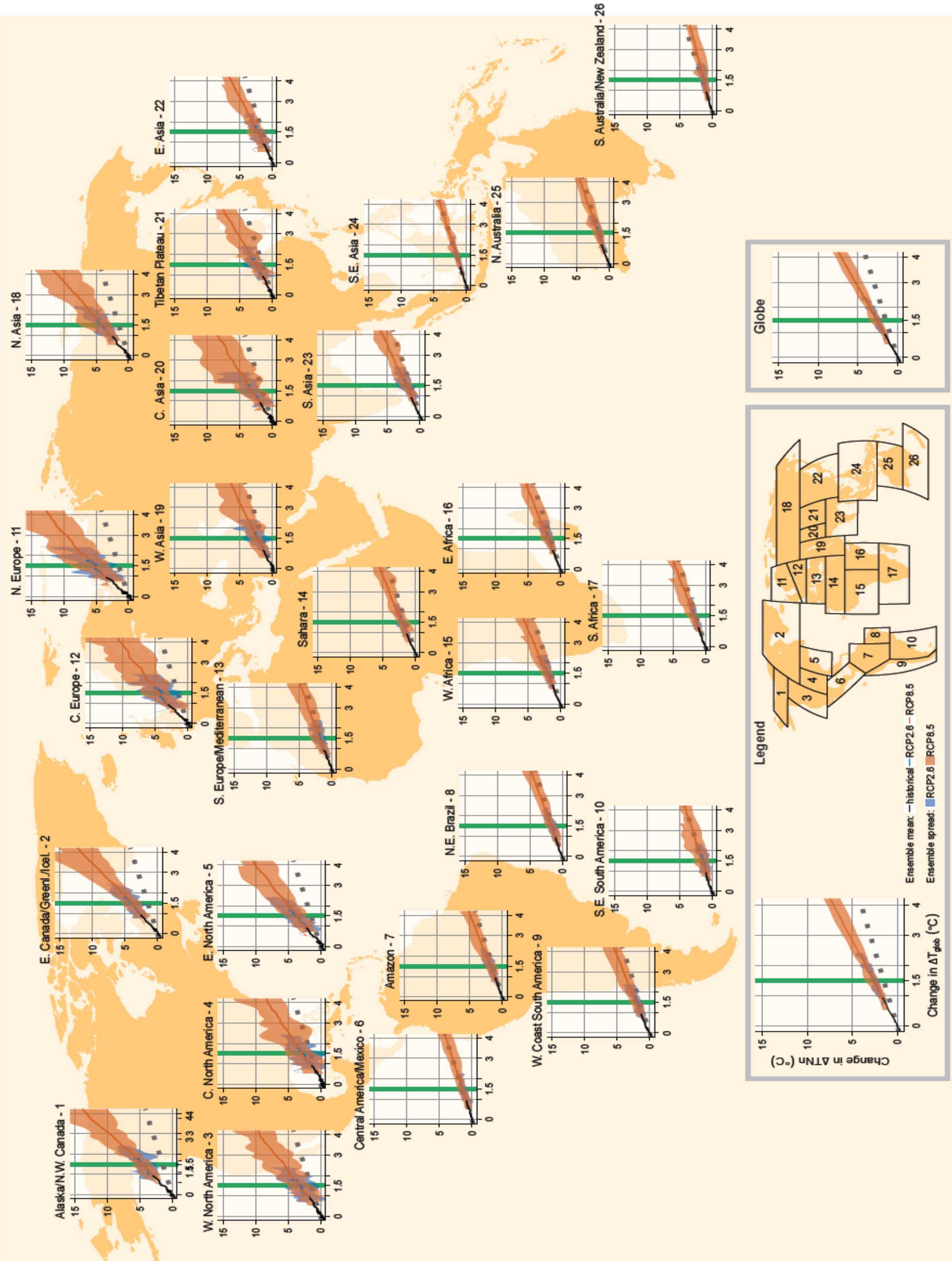


Figure 3.7: Projected changes in annual minimum nighttime temperature (TNn) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger and et al).

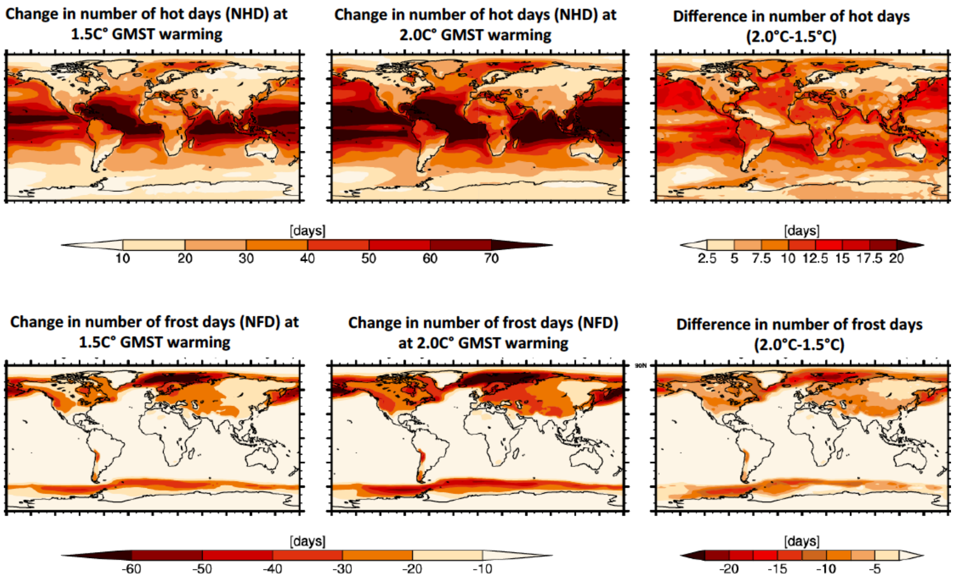


Figure 3.8: Projected changes in number of hot days (10% warmest days) and in number of frost days (days with T<0°C) at 1.5° (left) and 2°C (right) GMST warming, and their difference (right). Adapted from (Wartenburger and et al)

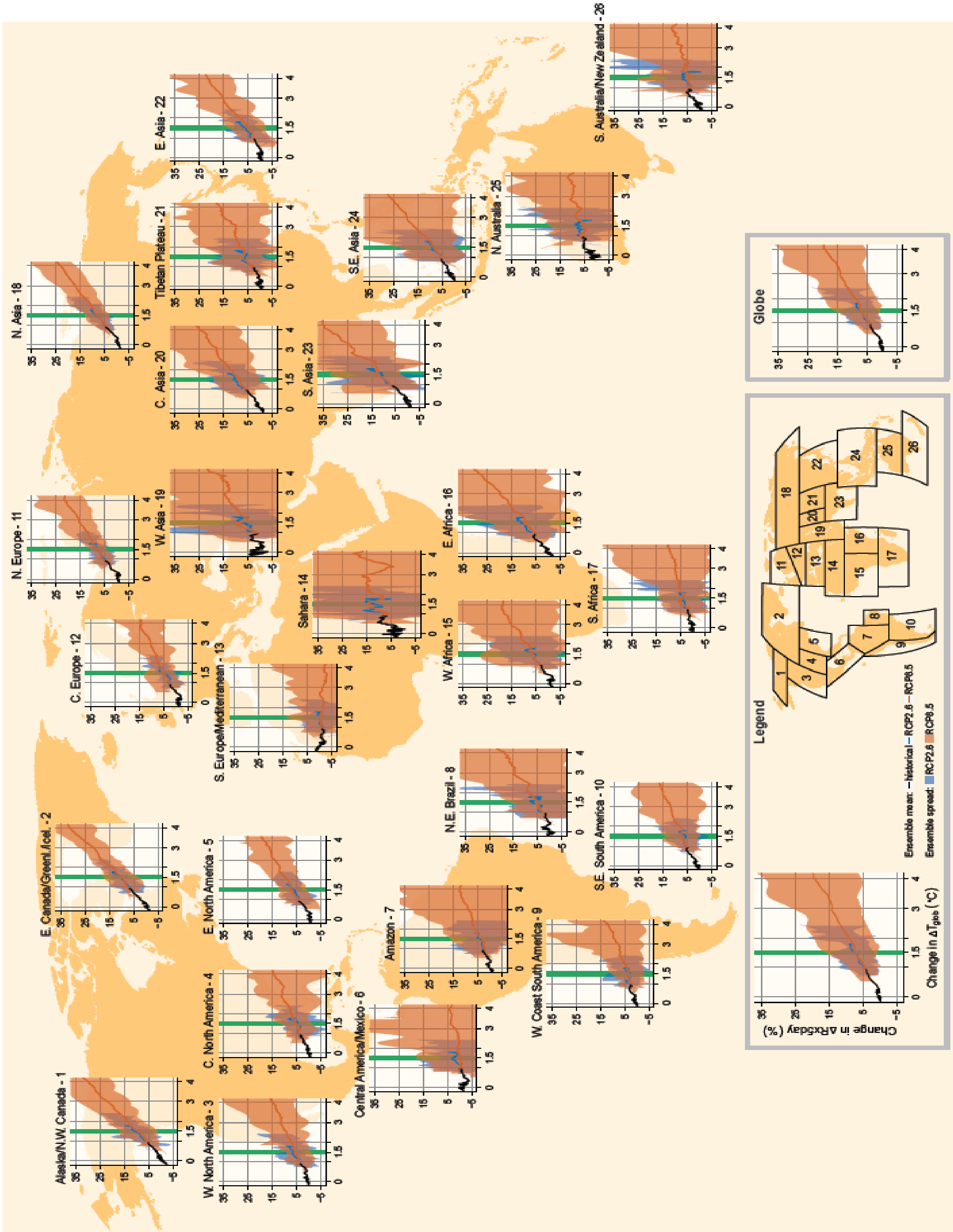


Figure 3.9: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC SREX regions. Adapted from Seneviratne et al. (2016) and (Wartenburger and et al).

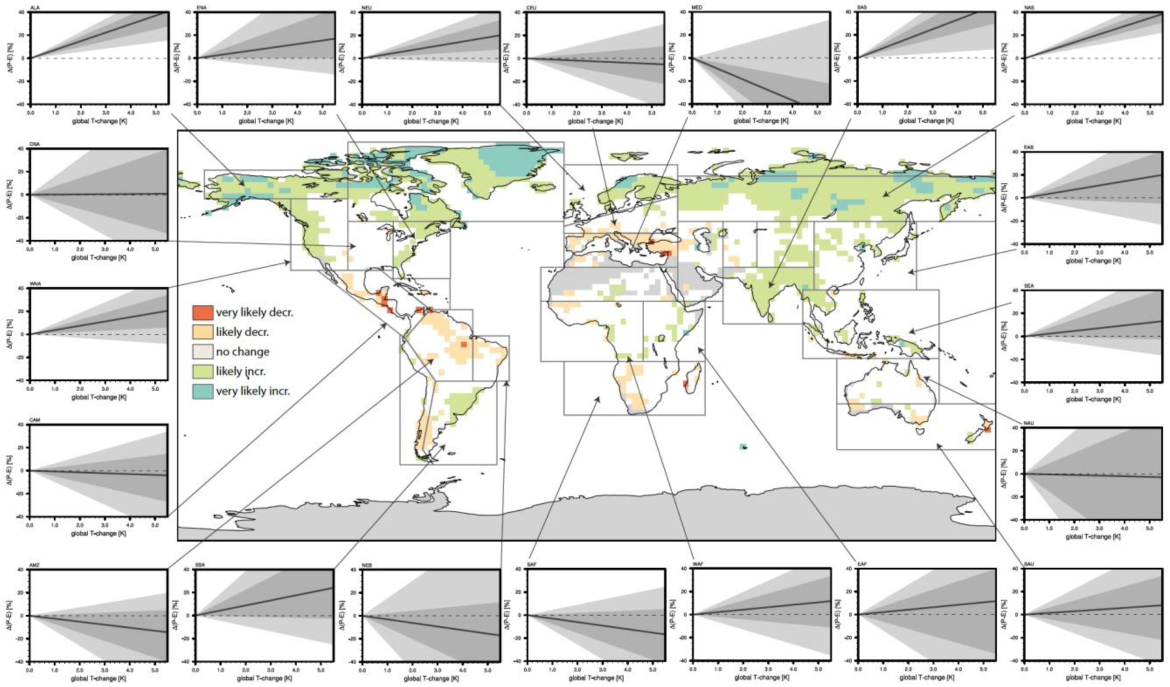


Figure 3.10: Conceptual summary of the likelihood of increases/decreases in P-E considering all climate models and all scenarios. Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean temperature change averaged for each SREX regions outlined in the map (from Greve submitted).

[PALCEHOLDER]

Figure 3.11: How reasons for concern accrue with global warming of between 0 and 2 °C above pre-industrial levels. The portion of the diagram that relates to warming of 1.5 °C versus 2 °C is magnified.

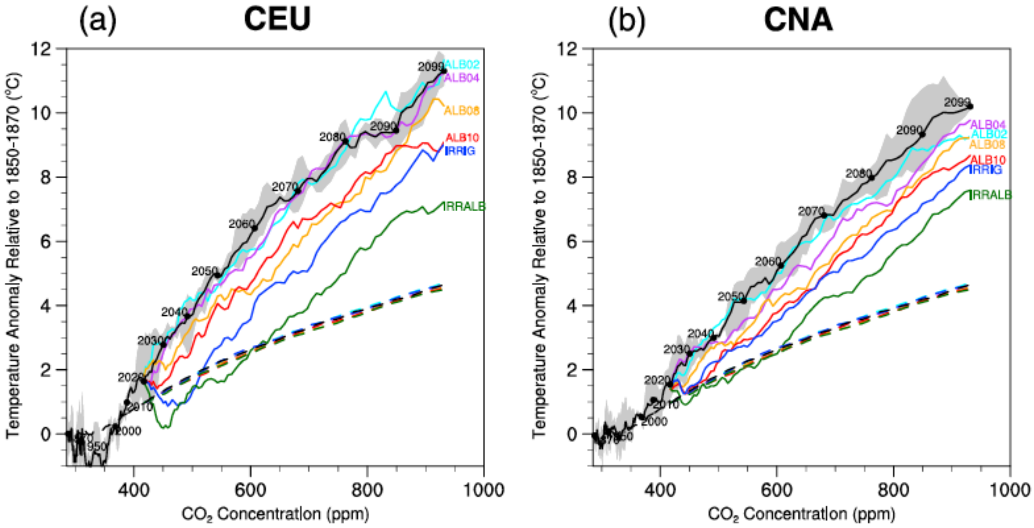
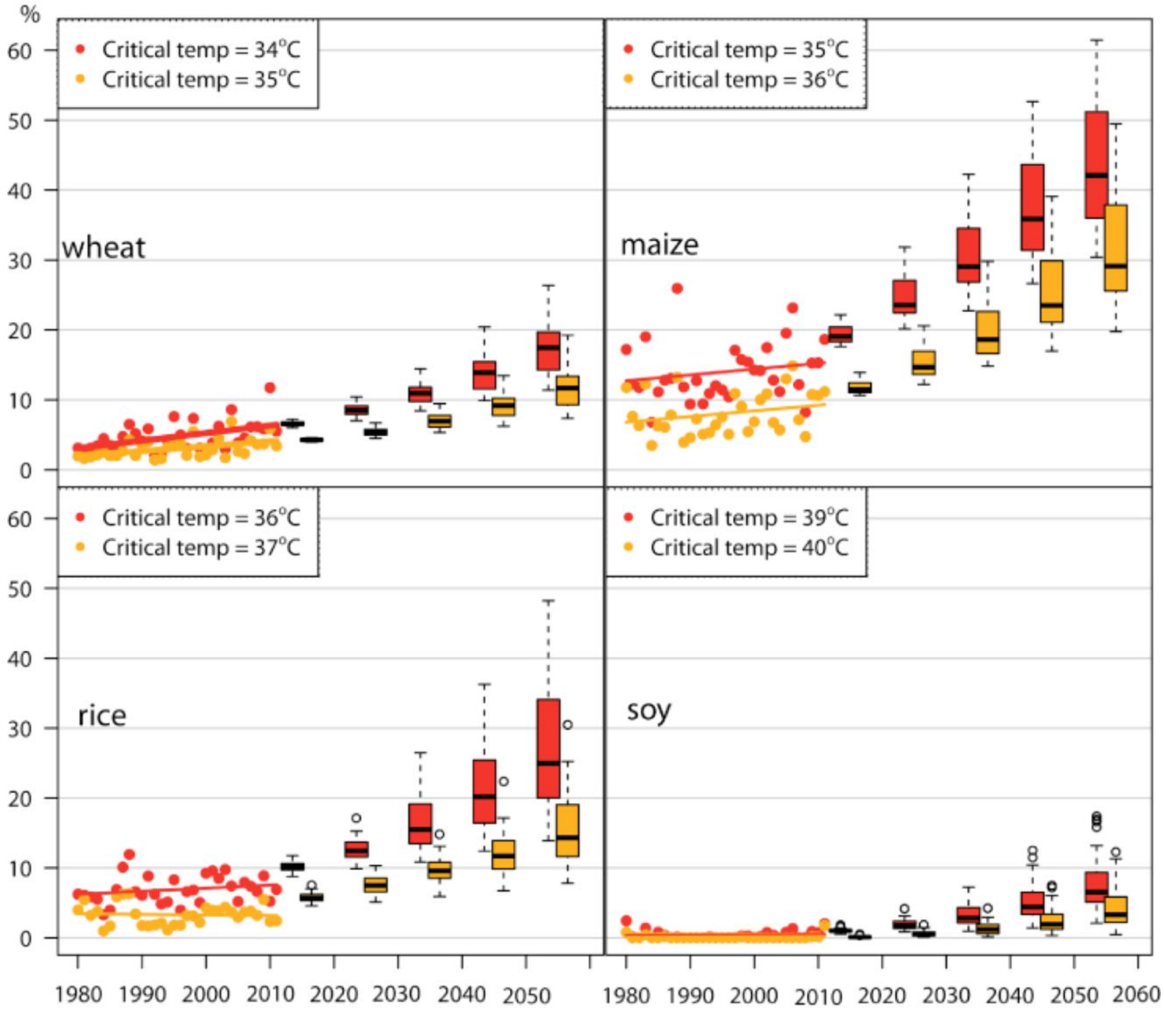


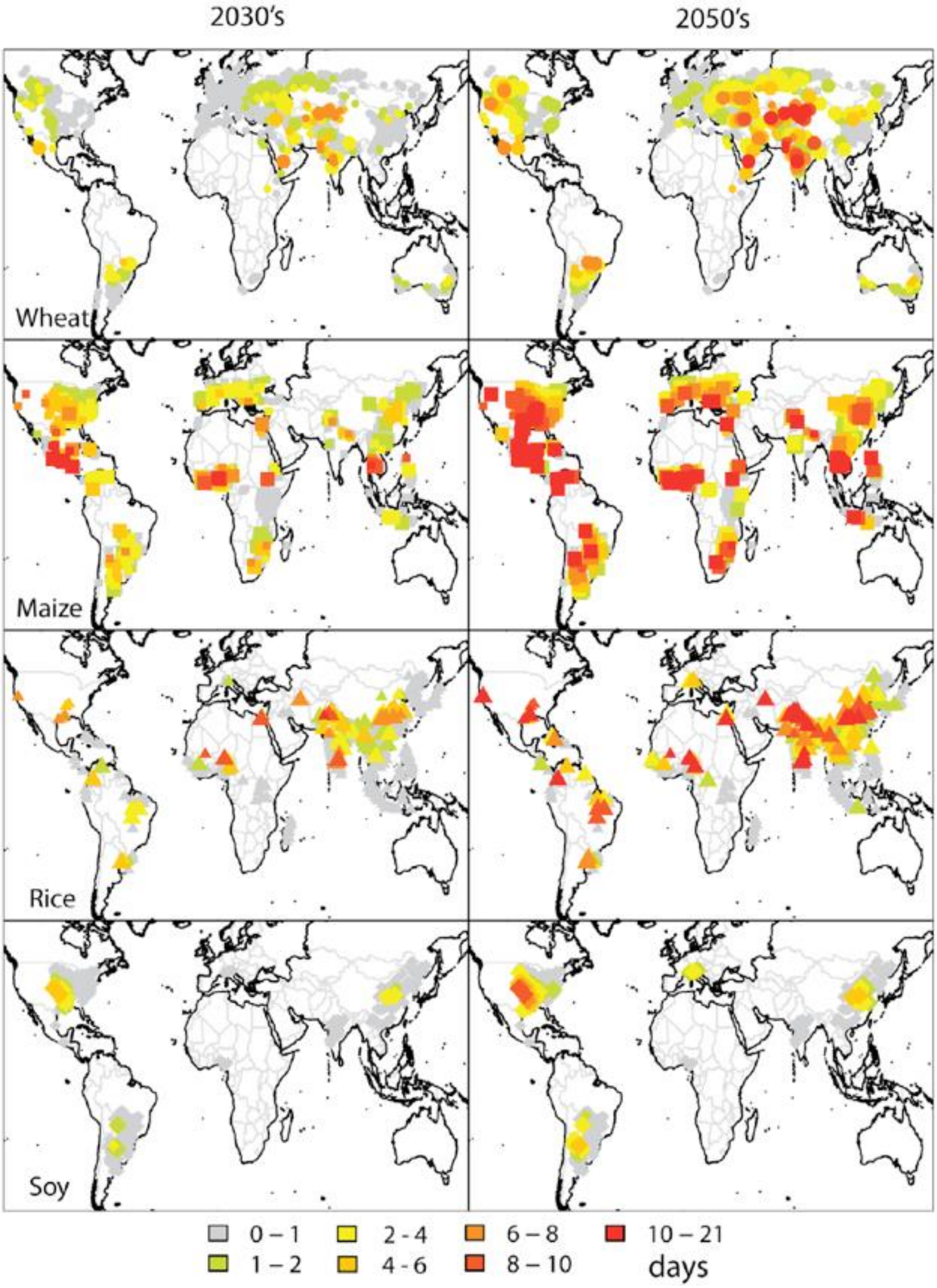
Figure 3.12: Regional temperature scaling with CO2 concentration (ppm) over 1850 to 2099 for two different SREX regions: Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850-1870 and units are in ˚C. The black line in all panels denotes the 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation on (blue), and irrigation with albedo +0.10 (green). Adapted from Figure 3 of Hirsch et al. (2017).

Box Figures

[PALCEHOLDER]
Box 3.1, Figure 1: Time series of precipitation in Middle East 3000 BP and 20-21st century



Box 3.4, Figure 1: Percent of total harvested area with at least 1, 5, or 10 reproductive days above the threshold over the recent past, as well as five decadal increments through 2050. Source: Figure 4 in Gourdji, et al., 2013.



Box 3.4, Figure 2: Geographically differentiated projections for the 2030's (left column) and 2050's (right column) in reproductive days over the critical temperature thresholds during flowering for all four crops along from the CMIP5 models for scenario A1B. Source: Figure 3 in Gourdji, et al., 2013)

Chapter 5

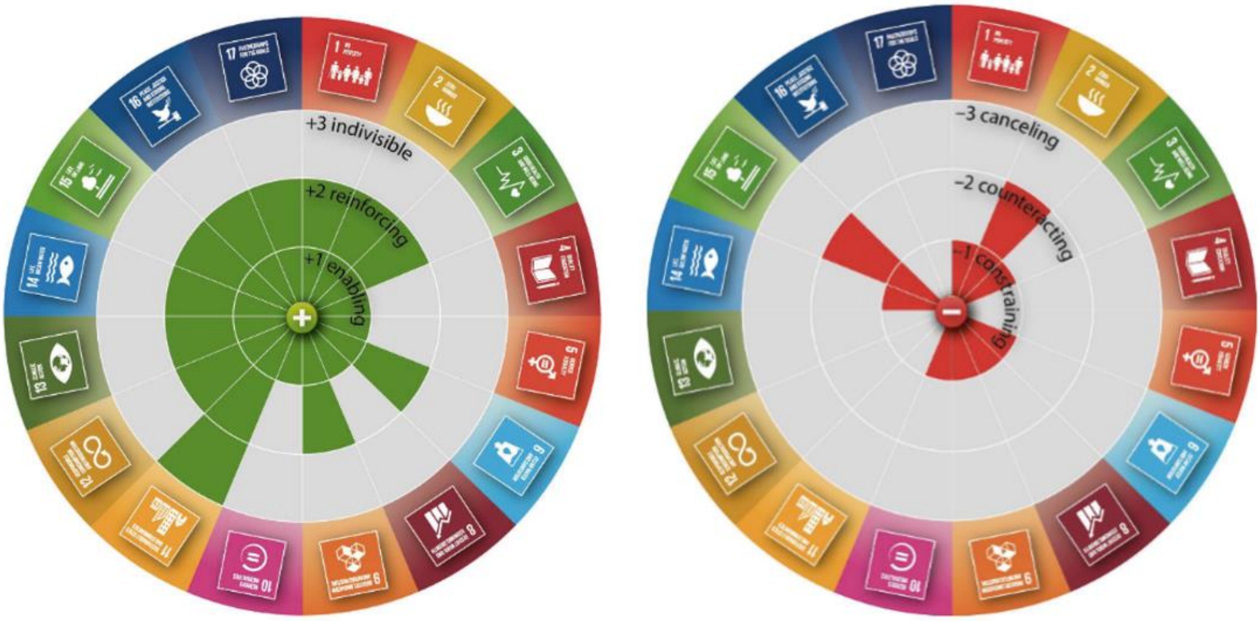


Figure 5.1: Nature of the positive (green) and negative (red) interactions between SDG 7 (Energy) and the 16 non-energy SDGs (Source: McCollum et al. Under Review).

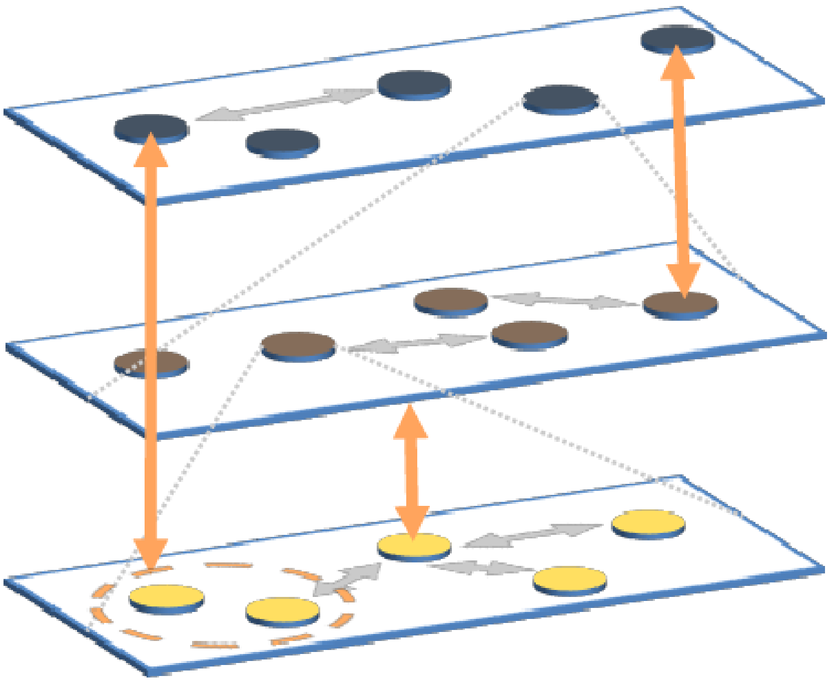


Figure 5.2: Schematic illustration of scalar interactions (Source: Bahu et al. 2013)

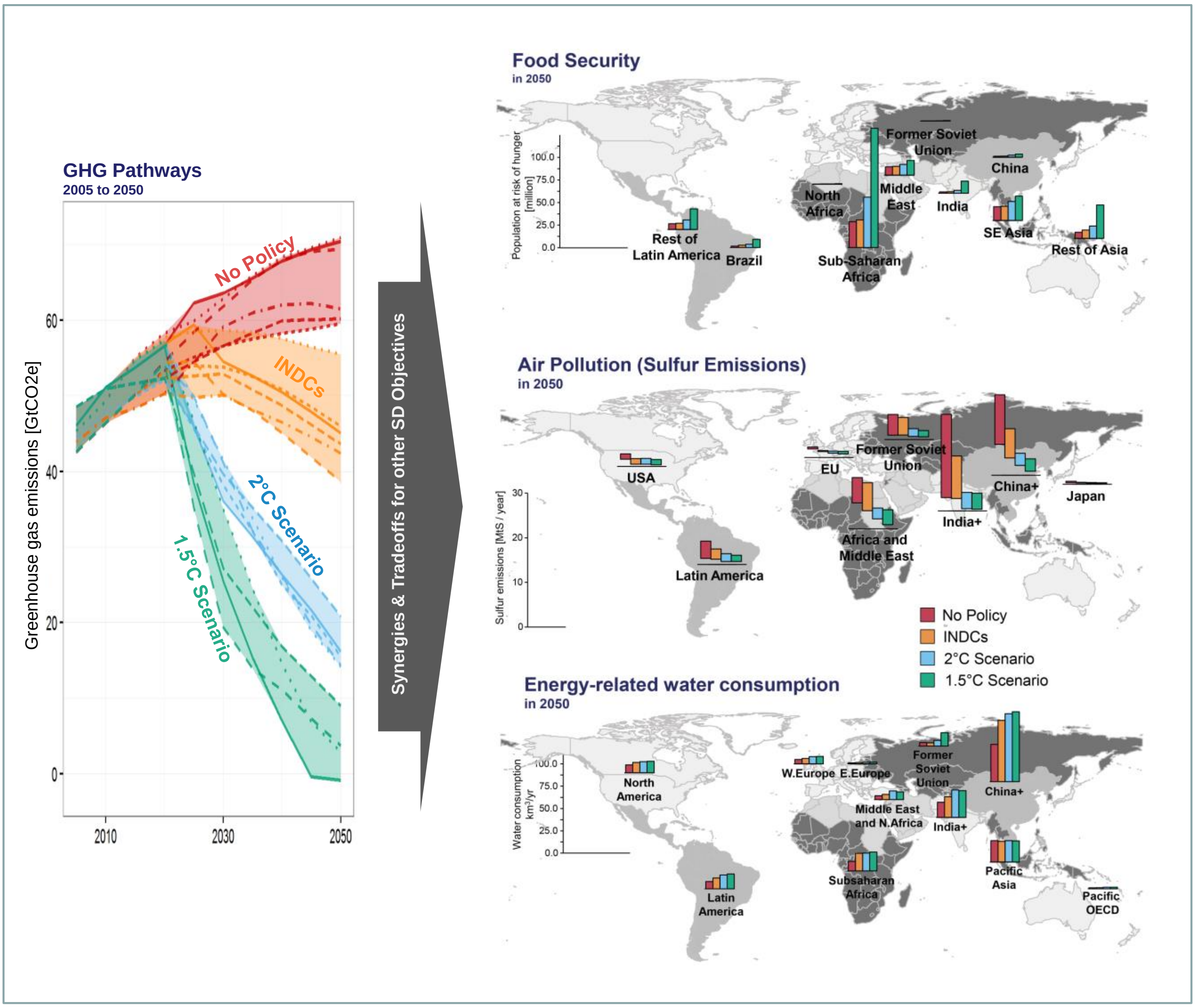


Figure 5.3: GHG emissions pathways and associated regional synergies and trade-offs for food security, air quality, and energy-related water consumption. Climate policy baseline pathways (No-Policy) are compared with INDC, 2°C and 1.5°C mitigation pathways. Sources: Fujimori et al, forthcoming (food security), Krey et al, forthcoming (Air pollution and water).

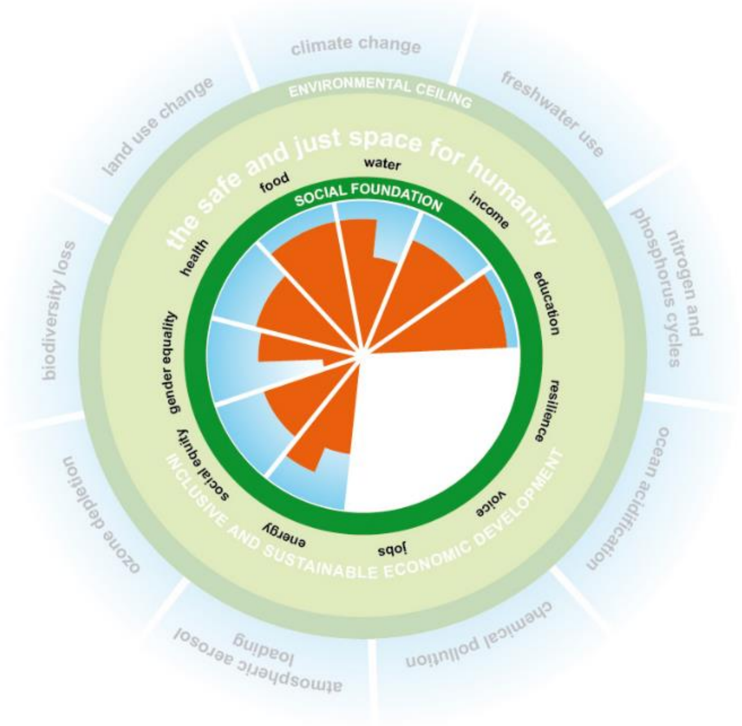
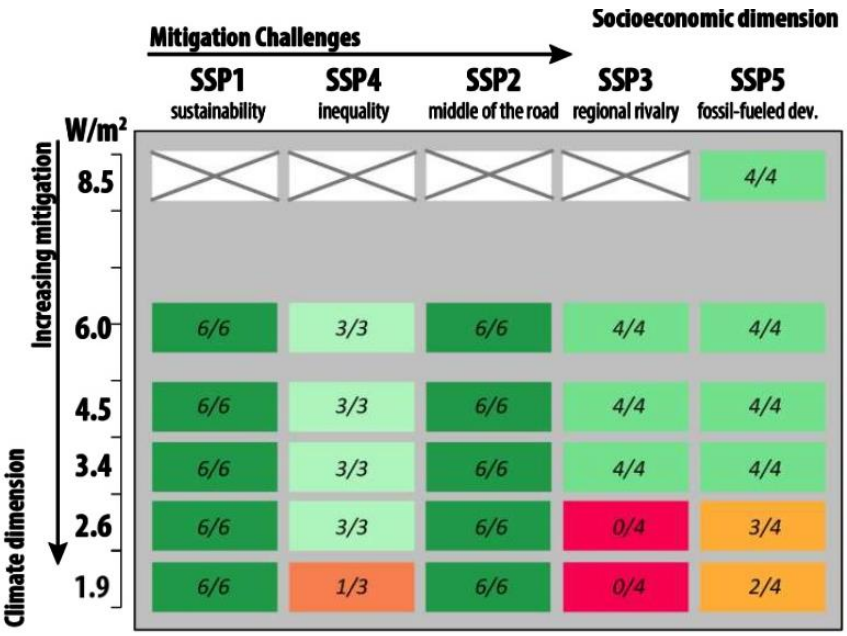
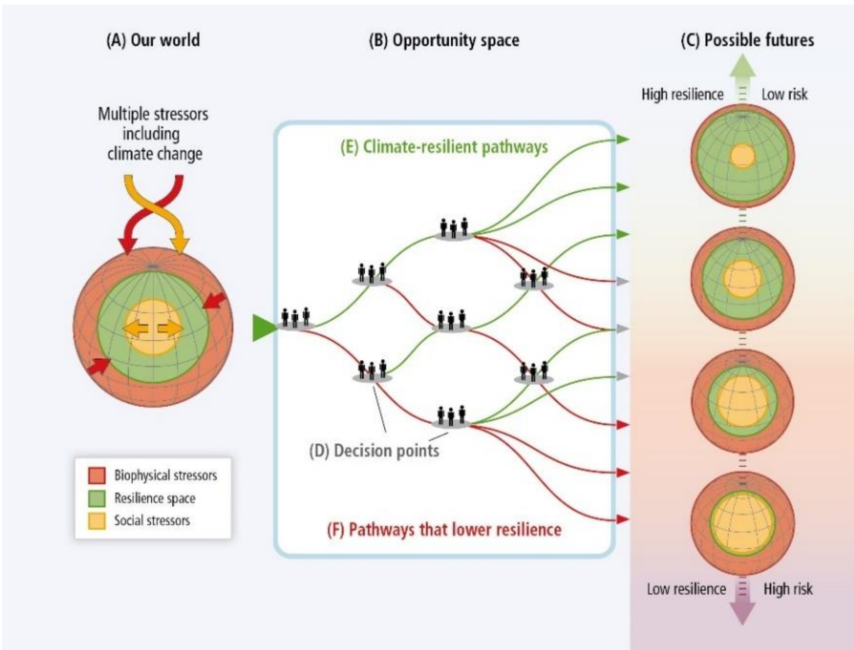


Figure 5.4: A safe and just space for humanity: Shortfalls on social foundations (Raworth 2012) – [*to be updated in April 2017*]



a)



b)

BOX 5.2, Figure 1: a) Roglej et al. (in preparation) – used in Ch2; b) Opportunity spaces and climate resilient pathways (IPCC 2014; Burkett et al. 2014)