Coupling dynamic models of climate and vegetation

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Abstract

Numerous studies have underscored the importance of terrestrial ecosystems as an integral component of the Earth’s climate system. This realization has already led to efforts to link simple equilibrium vegetation models with Atmospheric General Circulation Models through iterative coupling procedures. While these linked models have pointed to several possible climate–vegetation feedback mechanisms, they have been limited by two shortcomings: (i) they only consider the equilibrium response of vegetation to shifting climatic conditions and therefore cannot be used to explore transient interactions between climate and vegetation; and (ii) the representations of vegetation processes and land-atmosphere exchange processes are still treated by two separate models and, as a result, may contain physical or ecological inconsistencies.

Here we present, as a proof concept, a more tightly integrated framework for simulating global climate and vegetation interactions. The prototype coupled model consists of the GENESIS (version 2) Atmospheric General Circulation Model and the IBIS (version 1) Dynamic Global Vegetation Model. The two models are directly coupled through a common treatment of land surface and ecophysiological processes, which is used to calculate the energy, water, carbon, and momentum fluxes between vegetation, soils, and the atmosphere. On one side of the interface, GENESIS simulates the physics and general circulation of the atmosphere. On the other side, IBIS predicts transient changes in the vegetation structure through changes in the carbon balance and competition among plants within terrestrial ecosystems.

As an initial test of this modelling framework, we perform a 30 year simulation in which the coupled model is supplied with modern CO₂ concentrations, observed ocean temperatures, and modern insolation. In this exploratory study, we run the GENESIS atmospheric model at relatively coarse horizontal resolution (4.5° latitude by 7.5° longitude) and IBIS at moderate resolution (2° latitude by 2° longitude). We initialize the models with globally uniform climatic conditions and the modern distribution of potential vegetation cover. While the simulation does not fully reach equilibrium by the end of the run, several general features of the coupled model behaviour emerge. We compare the results of the coupled model against the observed patterns of modern climate. The model correctly simulates the basic zonal distribution of temperature and precipitation, but several important regional biases remain. In particular, there is a significant warm bias in the high northern latitudes, and cooler than observed conditions over the Himalayas, central South America, and north-central Africa. In terms of precipitation, the model simulates drier than observed conditions in much of South America, equatorial Africa and Indonesia, with wetter than observed conditions in northern Africa and China.

Comparing the model results against observed patterns of vegetation cover shows that the general placement of forests and grasslands is roughly captured by the model. In addition, the model simulates a roughly correct separation of evergreen and deciduous forests in the tropical, temperate and boreal zones. However, the general patterns of
global vegetation cover are only approximately correct: there are still significant regional biases in the simulation. In particular, forest cover is not simulated correctly in large portions of central Canada and southern South America, and grasslands extend too far into northern Africa.

These preliminary results demonstrate the feasibility of coupling climate models with fully dynamic representations of the terrestrial biosphere. Continued development of fully coupled climate-vegetation models will facilitate the exploration of a broad range of global change issues, including the potential role of vegetation feedbacks within the climate system, and the impact of climate variability and transient climate change on the terrestrial biosphere.

Keywords: biosphere–atmosphere interactions, climate–vegetation feedback, coupled models

Introduction

The Earth’s physical climate system and biosphere coexist within a thin spherical shell, extending from the deep oceans to the upper atmosphere, that is driven by energy from the sun. The resulting interactions among the atmosphere, oceans, and terrestrial ecosystems give rise to the biogeochemical, hydrological, and climate systems that support life on this planet. During the last few centuries, both the terrestrial biosphere and physical climate system have been undergoing fundamental changes in response to human activity. It is therefore of paramount importance to improve our understanding of global-scale climatic and biospheric processes.

The Earth’s climate is, in part, controlled by the fluxes of energy, water, and momentum across the lower boundary of the atmosphere. Over the oceans, the exchange of energy and water with the atmosphere depends primarily on the sea-surface temperature. Fluxes over land, on the other hand, are controlled by a more complex set of attributes, including the state of the vegetation cover and soils. Changes in vegetation, whether driven by climate or human activities, can substantially alter the physical characteristics of the land surface, potentially leading to large feedbacks on the atmosphere. In fact, a number of recent studies have suggested that feedbacks from changing global vegetation patterns may have played an important role in determining climatic conditions during the recent geological past:

- Possible role of vegetation feedbacks in initiating glaciations. Gallimore & Kutzbach (1996) and de Noblet et al. (1996) have indicated how changes in the position of the boreal forest – tundra boundary (and the associated differences in surface albedo between dark evergreen forests and snow-covered tundra), may be partially responsible for initiating ice age conditions during the Quaternary. According to this hypothesis, orbital variations and lower CO₂ concentrations initiate a trend towards glacial conditions, which is strongly amplified through the expansion of highly reflective tundra into the darker boreal forests. Previous climate modelling studies, which neglected the potential for vegetation feedbacks, generally failed to produce the conditions necessary to initiate past glaciations.

- Boreal forest feedbacks on early Holocene warming. In another set of palaeoclimate sensitivity studies, Foley et al. (1994) and TEMPO Authors (1996) discussed how a poleward shift in the boreal forest – tundra boundary during the early and middle Holocene epoch (roughly 6000–9000 years before present) may have strongly amplified orbitally induced warming of the high northern latitudes. Once again, the vegetation feedback mechanism acts to amplify an initial shift in climate through changes in surface albedo associated with tundra and boreal forest ecosystems. This vegetation feedback mechanism, which may strongly amplify high-latitude warming, should be further examined in terms of future climate change scenarios.

- A ‘green sahara’ and the African monsoon of the early Holocene. Finally, Kutzbach et al. (1996) and Claussen & Gayler (1997) have evaluated how the orbitally enhanced monsoon rains of northern Africa may have been amplified through vegetation feedbacks. The geological record indicates that the Sahara of the early and middle Holocene was a much wetter and more productive environment than present, with extensive grasslands, savannas and lakes (e.g. COHMAP Authors 1988). Such changes in the land surface (and the associated changes in albedo, leaf area, rooting depth, soil moisture, and evapotranspiration) may have enhanced the strength of the African monsoon. The same mechanism (but acting in reverse) was suggested by Charney et al. (1975) to explain increasing droughts in the Sahel in terms of anthropogenic desertification.

These palaeoclimate sensitivity studies, which have been partially corroborated by geological evidence, pro-
vide a very powerful motivation to further examine climate and vegetation interactions. In particular, future global change scenarios must be re-evaluated to consider the potential for vegetation feedback mechanisms. For example, scenarios of CO₂-induced global warming, already amplified in the high latitudes by snow and sea-ice feedbacks, may be substantially modified by long-term changes in the boreal forest and tundra boundaries.

Furthermore, several AGCM simulations have indicated that continental interiors may become much drier in response to global warming conditions, but this result has not considered the potential feedbacks caused by changes in vegetation cover. In addition, it is hypothesized that the physiological effects of increasing atmospheric CO₂ concentrations could significantly influence terrestrial vegetation by decreasing stomatal conductance and increasing canopy leaf area (Field et al. 1995), which may also give rise to significant feedbacks on the atmosphere (Pollard & Thompson 1995; Friend & Cox 1995; Henderson-Sellers et al. 1995; Sellers et al. 1996; Betts et al. 1997). Clearly, models used to simulate future climate must be improved to consider changes in vegetation cover, and their consequent feedbacks on the atmosphere.

**Linking climate and vegetation models**

When considering the potential interactions between vegetation and the atmosphere, we may distinguish between: (i) the rapid biophysical processes of energy, water, carbon, and momentum exchange; and (ii) the long-term interactions which arise from fundamental changes in the vegetation cover. For over a decade, many AGCMs have used land surface parameterizations (e.g. BATS of Dickinson et al. 1986; SiB of Sellers et al. 1986) to represent the rapid biophysical exchanges of energy, momentum, and water between terrestrial ecosystems and the atmosphere (Sellers et al. 1997). Until recently these land surface parameterizations have been operated by fixing the geographical distribution of vegetation types (Fig. 1a). Typically, each land gridcell of the AGCM is assigned a single vegetation type (e.g. tropical rainforest, boreal forest, tundra, desert), which has an associated set of biophysical characteristics, including leaf area index, albedo, rooting depth, and roughness length. However, using fixed patterns of global vegetation within climate models severely limits their use in studies of global environmental change.

During the last few years, a few preliminary attempts at linking models of vegetation cover to AGCMs have been made. Henderson-Sellers (1993) pioneered this work by operating the CCM1-Oz AGCM in conjunction with the Holdridge (1947) equilibrium vegetation scheme. In this study, the Holdridge scheme is applied annually to update the geographical distribution of vegetation types within the climate model. More specifically, the two models are iteratively linked through an equilibrium asynchronous coupling procedure (Fig. 1b), where a single year of the climate model simulation is used to drive changes in the equilibrium distribution of vegetation types which, in turn, are fed back into the AGCM land surface package. In principle, this iterating cycle of equilibrium climate and equilibrium vegetation simulations is repeated until the results of both models converge to some final state. In this initial study, Henderson-Sellers found that the coupled behaviour of the CCM1-Oz and Holdridge models was stable, with no particular trends or instabilities in the climate-vegetation system. In addition, she found only regional-scale differences in the simulation of modern climate between simulations performed with and without interactive vegetation cover.

In another effort to link climate and equilibrium vegetation models, Claussen (1994) performed several simulations with the ECHAM AGCM linked to the BIOME equilibrium vegetation model of Prentice et al. (1992). Like Henderson-Sellers, Claussen also employed an iterative equilibrium asynchronous coupling procedure to link the climate and equilibrium vegetation models. However, in Claussen’s study the BIOME model was driven by multiyear averages of the climate simulation, rather than the single-year climate simulations used in Henderson-Sellers (1993). Claussen also investigated the sensitivity of the coupled climate-vegetation to the specification of initial conditions. In particular, he compared the results of two coupled simulations: one initialized with the observed geographical distribution of vegetation types, and another initialized with tropical forests replaced with subtropical deserts and subtropical deserts replaced with tropical forests. His results showed that the equilibrium climate was affected by the initial vegetation conditions to permit savannas to persist in the desert of southwestern Sahara. These results suggest that the coupled climate-vegetation system, like many other nonlinear systems, may arrive at different equilibrium states depending on the choice of initial conditions.

A few other studies have applied asynchronously linked climate-vegetation models to issues of climate change. For example, de Noblet et al. (1996) linked the BIOME equilibrium vegetation model to the LMD AGCM to examine how changes in the boreal forest and tundra boundary may have contributed to the initiation of glaciations during the Quaternary. Claussen (1998), Claussen (1997), and Claussen & Gayler (1997) used the coupled ECHAM-BIOME model to investigate the influence of initial vegetation conditions on changes in the African and Indian monsoon during the modern and middle Holocene eras. Finally, Betts et al. (1997) have used coupled climate-vegetation models to investigate...
Fig. 1 Methods of coupling climate and vegetation models.

The potential role of vegetation feedbacks on future climatic change.

These exploratory studies all underscore the importance of incorporating representations of changing vegetation cover within climate models. However, they leave several important areas open for further model development. In particular, the current set of linked climate-vegetation models have two major limitations:

(a) Most existing vegetation models simulate only the equilibrium response of vegetation cover to changes in climate. Models, like BIOME and the Holdridge scheme, are unable to simulate transient changes in vegetation cover in response to shifting environmental conditions, such as changing climate and CO₂ concentrations. Therefore, current vegetation models cannot address the time-dependent nature of the atmosphere–biosphere response to climate variability or future climatic change.

(b) Vegetation models and AGCM land surface parameterizations are not always physically consistent. For example, in the coupled ECHAM-BIOME model, there are two independent treatments of the surface water and energy balance: one for describing land–atmosphere exchange processes (in ECHAM) and another for estimating the soil moisture requirements of plants (in BIOME). In ECHAM evapotranspiration is calculated on an 80 minute timestep using a detailed aerodynamic flux formulation, while BIOME calculates evapotranspiration once a day using a modified Priestley–Taylor formulation linked to a soil water balance model (Claussen, pers. comm.). An additional limitation of most equilibrium
vegetation models is that they do not explicitly consider structural attributes of vegetation, like leaf area index and vegetation height, which are often required by AGCM land surface parameterizations. Ideally, land surface physics, ecological processes, and vegetation structure should be simulated within a single, physically consistent model (Foley 1995).

To address these issues, a new group of fully dynamic biosphere models has recently emerged. These state-of-the-art models, often called Dynamic Global Vegetation Models (DGVMs), are designed to provide a more integrated and physically consistent simulation of land surface physics, ecological processes, and vegetation structure. Most importantly, DGVMs are also capable of simulating transient changes in ecosystem processes and vegetation structure (Steffen et al. 1992; Walker 1994). Some DGVMs, including the Integrated Biosphere Simulator (IBIS) of Foley et al. (1996), are also designed to be incorporated directly within AGCMs, thus providing a more complete linkage between atmospheric and ecological processes (Fig. 1c). IBIS has already been used off-line of an AGCM to investigate global patterns of water balance, primary productivity, and vegetation dynamics (Foley et al. 1996), and the potential impact of increasing CO2 concentrations on the hydrology of the Amazon basin (Costa & Foley, 1997). Here we present a new modelling framework for simulating atmosphere–biosphere interactions. Specifically, we have directly coupled the GENESIS global climate model to the IBIS dynamic global vegetation model.

IBIS — a dynamic global vegetation model for climate studies

IBIS (version 1) is designed around a hierarchical modelling framework (Fig. 2), in which information flows between various subsystems at appropriate frequencies. IBIS represents a number of land surface and ecosystem phenomena, including:

- **land surface and physiological processes**, including photosynthesis, respiration, and stomatal behaviour, as well as the surface energy, water, and momentum balance
- **phenological behaviour of leaf display and plant activity** in response to changing climatic conditions
- **transient changes in carbon balance and vegetation structure** resulting from changes in primary productivity, competition, carbon allocation, carbon turnover, and mortality

**Land surface processes and phenology**

IBIS includes a land surface module which simulates the energy, water, carbon, and momentum balance of the soil–vegetation–atmosphere interface. This module borrows most of its basic structure from LSX (Pollard & Thompson 1995; Thompson & Pollard 1995a,b), which is the original land-surface parameterization scheme of the GENESIS climate model. Here the land-surface module operates on a relatively short timestep (30 min), which is also the timestep used by the AGCM to simulate atmospheric dynamics. The module represents two vegetation layers (i.e. ‘woody plants’ and ‘herbaceous plants’) and six soil layers to simulate soil temperature, soil water, and soil ice content over a total depth of 4.25 m. Physical processes in the vertical soil column include heat diffusion, liquid water transport, uptake of liquid water by roots for transpiration, and the freezing and thawing of soil ice.

Physiologically based formulations of C3 and C4 photosynthesis (Farquhar et al. 1980; Collatz et al. 1991, 1992), stomatal conductance (Leuning 1995) and respiration (Amthor 1984) are used to simulate canopy gas exchange processes. This approach provides a mechanistic link between the exchange of water and CO2 between vegetation canopies and the atmosphere (Collatz et al. 1991; Sellers et al. 1992; Amthor 1994; Bonan 1995). Because of the nonlinear response of physiological parameters to varying environmental conditions, leaf-level processes are scaled to the canopy by assuming that the vertical profile of Rubisco capacity is nearly optimized with respect to net canopy photosynthesis (Field 1983; Sellers et al. 1992; Haxeltine & Prentice 1997).

Currently, IBIS uses very simple temperature and productivity criteria to control leaf display in winter-deciduous and drought-deciduous trees. While these algorithms reflect some basic control of climate on phenology, they could be improved to consider more processes, including the relationships between growing degree day requirements for budburst and chilling period length (e.g. Murray et al. 1989).

**Vegetation structure**

While previous vegetation models have focused on equilibrium vegetation patterns (e.g. Holdridge 1947; Prentice et al. 1992; Neilson & Marks 1994; Haxeltine & Prentice 1996), recent efforts have produced more highly generalized approaches to simulating vegetation dynamics in a wide range of environmental conditions. For global-scale applications, IBIS uses a simplified representation of vegetation dynamics where plant growth and competition are characterized by the ability of plants to capture light and water from common resource pools. For example, tall woody plants (trees and shrubs) intercept light first, and therefore shade herbaceous plants. However, herbaceous plants are able to preferentially capture soil moisture as it infiltrates through the soil. In this way, the model can simulate some of the basic features of competition between trees and herbaceous plants. Furthermore, competition among woody plants and among herbaceous plants is driven by differences in the annual carbon
Fig. 2 Overview of the IBIS dynamic global vegetation model. IBIS represents a number of ecosystem processes occurring at different timescales. Land surface physics and canopy physiological processes are simulated on a short timestep (30 min), while vegetation phenology and vegetation dynamics are simulated on longer timesteps (1 day and 1 year, respectively).

Balance resulting from differences in allocation, phenology, leaf form, and photosynthetic pathway. Unlike most other ecosystem models, IBIS explicitly simulates light and water availability as part of the physics of the land surface package during each 30 minute timestep.

In IBIS the vegetation cover is represented as a combination of nine plant functional types (7 trees and 2 herbaceous plants) that are adapted from Prentice et al. (1992). Plant functional types are defined to resolve a few important features: basic physiognomy (e.g. trees and grasses), leaf habit (e.g. evergreen and deciduous), photosynthetic pathway (C3 and C4), and leaf form (broad-leaf and needle-leaf) (Woodward & Cramer 1996). In order to determine which plant functional types may potentially exist within each gridcell, the model uses a set of simple climatic constraints (i.e. winter temperature limits, growing degree days, and minimum chilling requirements). In off-line simulations, IBIS uses long-term climatic means to determine the limits of each plant functional type. However, when coupled to an AGCM, IBIS uses a 5-year running mean of the monthly average climatic parameters.

While IBIS-1 correctly simulates the basic global-scale patterns of ecosystem processes and vegetation cover (Foley et al. 1996), the current version of the model has several limitations, including a lack of explicit disturbance mechanisms (e.g. fire and windthrow). This omission has important consequences on the ability of the model to describe savannas and mixed forests, whose composition is strongly affected by disturbance frequency. We also expect that the representation of vegetation dynamics could be improved by including parameterizations of other subgrid and landscape-scale processes (Walker 1994).

**GENESIS — a global climate model**

The global climate model used here is version 2 of the GENESIS (Global ENvironmental and Ecological Simulation of Interactive Systems) AGCM, which was developed at the National Center for Atmospheric Research (NCAR) for the main purposes of performing greenhouse and palaeoclimatic experiments. An earlier version of the model (version 1.02) has been described in Thompson & Pollard (1995a,b) and Pollard & Thompson (1994, 1995). The primary improvements to the model physics in version 2 are documented in Thompson & Pollard (1997), along with a discussion of the model’s present-day climate and polar ice-sheet mass balance. In addition, a few palaeoclimatic applications of version 2 are described in Pollard & Thompson (1997a,b). For brevity, only the most salient features of the model are outlined below.

The atmospheric component of GENESIS is a 3D spectral general circulation model, which is nominally
operated at T31 spectral horizontal resolution (∼3.75° latitude by 3.75° longitude), with 18 vertical levels, and an overall timestep of 30 min. In this exploratory study, we use a coarser configuration of R15 spectral resolution (∼4.5° latitude by 7.5° longitude) to save on computing expenses. We expect the GENESIS model’s simulation of modern-day climate to degrade as the resolution becomes coarser. Yet, for the purposes of illustrating the general behaviour of a coupled climate–vegetation model, this resolution should be sufficient.

Solar radiation is modelled using a delta-Eddington two-stream approximation for clear and cloudy fractions of each atmospheric layer, with cloud overlap assumed to be random between layers. The radiation code of the model treats the separate effects of greenhouse trace gases (CO₂, CH₄, N₂O, CFC11, and CFC12) explicitly, assuming globally uniform mixing ratios (Wang et al. 1991). O₃ is prescribed from 3D monthly average climatological fields (Wang et al. 1995). The radiative effects of tropospheric aerosols are also included, assuming a uniform aerosol column over all nonice land points, with a prescribed exponential decrease with height.

GENESIS uses prognostic 3D cloud water amounts to separately predict stratus, convective, and anvil cirrus clouds (Senior & Mitchell 1993; Smith 1990). A semi-Lagrangian algorithm is employed to transport water, while convective plumes and background diffusion mix water vertically. The model includes the processes of evaporation, conversion to precipitation, cloud droplet aggregation, and turbulent deposition of lowest-layer cloud particles onto the surface. The model physics also accounts for both ice and liquid cloud particles, but neglects the latent heat of freezing.

While the atmospheric portion of GENESIS operates at coarse (R15) to moderate (T31) resolutions, land and ocean surfaces are represented at a much finer spatial resolution of 2° latitude by 2° longitude. For each land gridcell, the topography and fraction of surface water are derived from the high-resolution U.S. Navy FNOC global elevation dataset (Cuming & Hawkins 1981; Kineman 1985). While GENESIS has been previously coupled to a variety of ocean models, in this study we prescribe monthly mean ocean temperatures from climatological data (Shea et al. 1992).

Results of the coupled simulation

In this simulation, the coupled GENESIS–IBIS model is run 30 years and is initialized with globally uniform air temperatures (15 °C), soil temperatures (15 °C), and soil moisture (50% of available pore space). The model’s vegetation cover is initialized from a modified version of Haxeltine & Prentice’s (1996) potential vegetation map. In particular, the Haxeltine & Prentice (1996) map is simplified to represent only 7 vegetation types, instead of the original 18 (Table 1). For each vegetation type, a set of leaf area index and biomass parameters are assigned following Table 1. To avoid artifacts of the initial vegetation map (e.g. unrealistically sharp boundaries between vegetation types), the resultant distributions of LAI and biomass are smoothed through a 3-cell by 3-cell spatial averaging filter.

During the first 10 years of the coupled model simulation, the model maintains the initial characteristics of the vegetation cover, so that the atmospheric circulation will be allowed to equilibrate without interactive vegetation. Starting in Year 11, the coupled model allows the vegetation cover to change, directly responding to the simulated climate. Simultaneously, a 5-year running-mean of monthly temperatures and growing degree days is used to broadly bound the distribution of plant types. Clearly this way of applying climatic limits on the geographical distribution of plant types is not process-based, but rather a very rough approximation for how plant distributions respond to shifting climatic patterns. We plan to replace this with a more mechanistic formulation in a future version of the model, when we have explicit representations of these processes.

In this exercise we have not employed a ‘flux correction’ procedure, which is very common in atmosphere–ocean modelling (e.g. Meehl 1990). In most coupled atmosphere–ocean models, key variables at the atmosphere–ocean interface (i.e. sea surface temperature and salinity) are restored towards observed climatological values, so as to keep the coupled model from ‘drifting’ into a poor representation of the current climate. The main drawback of this procedure is that it lacks a physical basis. Furthermore, it is unclear how one would restore a coupled atmosphere–biosphere model towards observations, because the system interface cannot easily be characterized by only a few well-observed parameters. As a result, we have decided not to use a flux correction technique to correct for biases in the AGCM and DGVM simulations. Thus we retain the physical consistency which this coupling scheme achieves. As coupled climate–vegetation models become more commonly used, this issue may need to be re-examined.

Simulated climate

According to Thompson & Pollard (1997), the present-day climate in GENESIS version 2 is significantly improved in many regions compared to the earlier results for version 1.02. Most of the improvements apparently stem from the greater horizontal and vertical resolutions, the new prognostic cloud scheme, and adjustments to the convective plume scheme. In particular, precipitation, high-latitude surface temperatures, and snow and sea-ice
Table 1 Initial vegetation types. The types of vegetation defined in the potential modern vegetation map used as initialization for this simulation. These vegetation types directly correspond to the types used by Haxeltine & Prentice (1996). Each vegetation type is assigned an upper canopy and a lower canopy initial LAI. In every continental gridcell, this LAI is partitioned among the IBIS plant functional types (pfts) permitted to exist according to simple climatic requirements (Foley et al. 1996). The resultant LAI maps for individual pfts are smoothed through a 3 by 3 low pass filter and converted into leaf carbon using specific leaf area values for each pft. Initial root carbon is assumed to equal initial leaf carbon. Initial wood carbon is such that in forests it adds up to 10 kg-C m\(^{-2}\).

<table>
<thead>
<tr>
<th>Simplified H &amp; P</th>
<th>H &amp; P types</th>
<th>Woody Tree LAI</th>
<th>IBIS tree pfts LAI (%)</th>
<th>Herb. LAI</th>
<th>Herb. biomass (kg-C m(^{-2})) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 EVERGREEN FOREST</td>
<td>2, 4, 6, 7, 8</td>
<td>6.0</td>
<td>10.0</td>
<td>75% evergreen</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25% deciduous</td>
<td></td>
</tr>
<tr>
<td>2 DECIDUOUS FOREST</td>
<td>1, 5, 9</td>
<td>6.0</td>
<td>10.0</td>
<td>25% evergreen</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75% deciduous</td>
<td></td>
</tr>
<tr>
<td>3 MIXED FOREST</td>
<td>3</td>
<td>6.0</td>
<td>10.0</td>
<td>50% evergreen</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50% deciduous</td>
<td></td>
</tr>
<tr>
<td>4 SAVANNA GRASSLAND</td>
<td>10, 11, 12, 13</td>
<td>0.5</td>
<td>0.8</td>
<td>50% evergreen</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50% deciduous</td>
<td></td>
</tr>
<tr>
<td>5 XERIC VEGETATION</td>
<td>14, 15</td>
<td>0.8</td>
<td>1.3</td>
<td>50% deciduous</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50% deciduous</td>
<td></td>
</tr>
<tr>
<td>6 TUNDRA</td>
<td>17</td>
<td>0.0</td>
<td>0.0</td>
<td>none</td>
<td>2.0</td>
</tr>
<tr>
<td>7 DESERT</td>
<td>16, 18</td>
<td>0.0</td>
<td>0.0</td>
<td>none</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The general distribution of surface air temperatures (Fig. 3) appears to be well captured by the model; however, a significant warm bias is noticeable in the high northern latitudes. Comparing the simulated surface air temperatures with observations of Legates & Willmott (1990, 1992) (Fig. 4), we see some significant regional-scale biases in the simulation. For example, there is a large cold bias in the northern hemisphere over the Himalayan plateau and China, which we attribute to erroneous wintertime dynamical effects of the Himalayan plateau. Large areas of the northern continental interiors are too warm, notably central Canada, Eastern Europe, and central Asia, which may have serious effects on the local vegetation. Despite these regional climatic biases, the zonal-average temperature fields (not shown) compare very favourably to observations and the results of other coarse-resolution GCMs.

The global-average precipitation rate in the simulation is 1095 mm y\(^{-1}\), which is within the range of observed climatologies (e.g. 1153 mm y\(^{-1}\), Legates & Willmott 1992). Over land, annual-average precipitation is 865 mm y\(^{-1}\) (compared to 806 mm y\(^{-1}\) and 864 mm y\(^{-1}\) according to Baumgartner & Reichel (1975) and UNESCO (1978), respectively), and annual evapotranspiration is simulated to be \(\approx 75\%\) of the precipitation (compared to 65% and 61%, according to Baumgartner & Reichel and UNESCO, respectively). While the zonal mean patterns of precipita-
The general distribution of surface air temperatures is well captured by the model; however, a significant warm bias is noticeable in the high northern latitudes. Surface fields from the atmosphere are passed to the surface grid (2° latitude by 2° longitude), where they are used in the surface physics and ecosystem dynamics calculations. There are a few areas whose annual rainfall is much less than observed, most notably the Amazon Basin and southern South America, central Africa and Indonesia, which may have serious effects on the vegetation cover. The model also tends to slightly underestimate rainfall over northern continental interiors between 40° and 60° N. The model simulates wetter than observed conditions in northern Africa and China. Work is in progress to improve these shortcomings; however, the general patterns of simulated precipitation are reasonably realistic for medium- to low-resolution AGCMs, and may be adequate for the initial exploration of vegetation–climate feedback mechanisms.

Simulated net primary productivity and vegetation cover

While this is a relatively long (30 year) simulation by most AGCM standards, it is important to note that the vegetation component of the coupled model has not fully reached equilibrium. By the end of the simulation, global net primary productivity (NPP) has roughly stabilized (Fig. 8a), but leaf area index (LAI) (Fig. 8b) and biomass (Fig. 8c) have not, particularly in regions which have experienced a large change in vegetation cover during the simulation. We expect, based on forest LAI and biomass data, as well as our experience with IBIS offline, that LAI will equilibrate after another decade or two, while biomass will equilibrate after a few more decades.
in the tropics and will continue to change for a century or more in slower-growing forests of cold climates.

Net primary productivity is often used as an index to compare ecosystem activity, and its relationship to climate. The global patterns of NPP (Fig. 9a) simulated by the coupled model are strongly driven by the modelled climate: areas of high NPP are in warm and moist climates, while the least productive areas include subtropical deserts, mountain ranges, and polar regions. In this simulation, global total NPP is 83 Gt-C y⁻¹, which is fairly high compared to other model-based estimates (e.g. Foley 1994). This value would have declined in a longer simulation due to the accumulation of respiring woody biomass.

The simulated vegetation cover may be represented by the geographical distributions of leaf area index (LAI) and biomass. The global distribution of total LAI (Fig. 9b) shows the relative density of vegetation cover, which is strongly determined by the modelled climate: areas of highest LAI include the rainforests of South America, Africa, and Asia, and forests of North America and East Asia. Total vegetation biomass (Fig. 9c) follows this same basic pattern, with high biomass in tropical and temperate forests, and low biomass in deserts and high-latitude areas.

While some very basic geographical patterns of global vegetation cover appear to be qualitatively captured by the coupled model, there are still many areas that are poorly simulated. For example, the forest and grassland cover is underestimated in a large section of South America as a result of the drier than observed conditions simulated by GENESIS. A similar bias in the climate model (i.e. warmer than observed temperatures, lower than observed precipitation) results in very low produc-
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Fig. 6 Simulated Patterns of Precipitation.

Activity and forest cover south-west of Canada’s Hudson Bay. Conversely, anomalously wet conditions permit grasslands to penetrate parts of the southern Sahara and Arabian deserts.

We may also compare the geographical distributions of LAI for individual plant types, to demonstrate that many basic patterns of vegetation geography are simulated fairly well by the coupled model (Figs 10 and 11). The model retains a clear separation of forests, grasslands, and tundra, with grasslands and tundra dominating the semiarid and high-latitude regions of the world. Grasslands are scattered throughout central Asia, central North America, central Australia, and the semiarid regions of Africa and South America. Because of the lack of natural disturbance mechanisms, particularly fire, the model does not simulate the large areas of savanna vegetation in Africa and South America.

In the forested portions of the world, the model clearly indicates a separation of evergreen-dominated and deciduous-dominated forests (Fig. 10a and b). For example, in the high-latitudes, the model successfully sustains a boreal deciduous (i.e. *Larix* dominated) forest in eastern Siberia, and evergreen-dominated forests throughout the rest of the circumpolar boreal zone. The mid-latitude forests of Europe, eastern North America, and east Asia are a mixture of evergreen and deciduous trees, but deciduous trees clearly dominate the core of the temperate forest regions (eastern North America, western Europe, and portions of east Asia). In the tropics, the model includes regions of drought deciduous forests in the areas of seasonal rainfall, and tropical evergreen forests in the core of annual rainfall in the Amazon basin, central Africa, and Indonesia. In south-central Africa, however, tropical deciduous trees are shown to give way to lush grasslands, because of cooler than observed temperatures in the region.
Fig. 7 Simulated minus observed patterns of precipitation. While the zonal patterns of precipitation agree well with observations (not shown), regional-scale differences between observed and simulated precipitation (plotted only over land) may be large. The model simulates drier than observed conditions in much of South America, equatorial Africa and Indonesia, with wetter than observed conditions in northern Africa and China. The model also tends to slightly underestimate rainfall over northern continental interiors between ~40° to 60° N. Observed precipitation rates are taken from the Legates & Willmott (1990, 1992) climate dataset.

Fig. 8 Simulated trends of (a) Net Primary Production (NPP), (b) Average Leaf Area Index (LAI), and (c) average biomass. The trend in the global total NPP (a) appears to roughly stabilize by the end of the simulation, while the trends in the LAI (b) and especially the biomass (c) do not.
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Fig. 9 Simulated patterns of (a) Net Primary Production (NPP), (b) Total Leaf Area Index (LAI), and (c) total biomass. The resulting patterns of NPP (a) in the coupled model (averaged between years 26 and 30) are strongly driven by the simulated climate: areas of high NPP are in warm and moist climates, while the least productive areas include subtropical deserts, mountain ranges, and polar regions. The same applies to total LAI (b) and total biomass (c).

Vegetation feedbacks on climate

To assess the potential feedbacks the interactive vegetation cover may have on the climate, we compare two periods of simulation: one with fixed vegetation (Years 6–10), and one with interactive vegetation (Years 26–30).

The interactive changes in vegetation cover result in significant (at the 95% confidence level) temperature changes in several regions (Fig. 12). For example, the changing vegetation cover causes cooling over the southern Sahara and Arabian deserts, mainly during the drier seasons (boreal autumn, winter, and spring), which can be attributed to the northward expansion of grasslands. In the early stages of the simulation, the model places a stronger than observed monsoon over northern Africa, permitting grasslands to penetrate northward. The ensuing changes in vegetation result in greater evapotranspiration, which in part explains lower temperatures during the drier times of year. Furthermore, greater amounts of atmospheric moisture may cause additional cloudiness, less solar radiation at the surface, and cooler temperatures. Conversely, a reduction in vegetation cover causes significant warming over south-central Africa in austral summer, over much of south-eastern South America in austral summer, and in central Asia during boreal summer. Differences in relative humidity (not shown) also show a clear signal of the effects of interactive vegetation, with moister conditions over much of the Sahara and Arabian deserts, and drier conditions in central Asia.

Changes in precipitation resulting from the interactive vegetation cover are not as clear at the 95% confidence level (Fig. 13). Most notably, we observe an increase in precipitation over part of the Sahara late in the wet season (boreal autumn) and the southern Arabian desert during the wettest season (boreal summer). The effects of interactive vegetation cover also cause significant increases in snow cover at the southern edge of the boreal forest and significant decreases in regions dominated by tundra (not shown). It is important to note that precipitation displays greater interannual variability than temperature and relative humidity, making it difficult for a t-test to capture the significance of the changes resulting from interactive vegetation.

Overall, the differences in climate resulting from interactive changes in vegetation cover are relatively small compared to the intrinsic biases of the AGCM. The largest changes in climate are associated with changes in the position of desert/grassland and forest/tundra ecotones, which have already been implicated as centres of action in previous climate-vegetation modelling studies (e.g. Claussen 1994; Foley et al. 1994).

Conclusions

Scenarios of future climate change must be re-evaluated to consider the potential for vegetation feedback mechanisms. In particular, the effects of several hypo-
thesized vegetation feedback mechanisms should be investigated, including: (a) changes in albedo resulting from shifting boreal forest and tundra boundaries, (b) changes in the extent of deserts and the resulting changes in albedo and evapotranspiration, (c) increases in mid-continental aridity, with the consequent changes in vegetation cover and soil moisture, and (d) changes in vegetation cover and evapotranspiration directly
Fig. 12 Differences in simulated temperature between interactive vegetation (Years 26–30) and Fixed Vegetation (Years 6–10) Conditions. To assess how the interactive vegetation cover may affect the overall climate of the model, we compare the surface air temperature patterns between interactive vegetation (Years 26–30) and fixed vegetation (Years 6–10) portions of the run. We employ a student $t$-test to assess the statistical significance (at the 95% level) of the differences in temperature. The significant changes in temperature are plotted only over land.

resulting from the physiological effects of increased CO$_2$ concentrations. Using coupled climate–vegetation models could help elucidate the role of vegetation feedback mechanisms on future climate.

Previous studies, including Henderson-Sellers (1993) and Claussen (1994), have demonstrated the feasibility of linking simple equilibrium vegetation models with atmospheric general circulation models. While these exploratory efforts have highlighted the importance of representing vegetation cover within AGCMs, they have suffered from two limitations: (a) the equilibrium nature of current vegetation models, and (b) possible inconsistencies between vegetation models and land surface parameterizations. Ideally, AGCMs should be directly coupled to fully dynamic and integrated models of the biosphere, where land surface physics, ecological processes, and vegetation dynamics would be simulated within a single, physically consistent framework (Foley 1995). Here we have taken the next logical step of coupling an AGCM with a fully dynamic and integrated global vegetation model.

In any coupled modelling exercise, it is important to examine the variability of the system across a wide variety of timescales. Unfortunately, this initial simulation is not long enough for us to judge whether the climate–vegetation system will remain stable around the simulated mean conditions or it will oscillate with a discernible long-term trend. Longer simulations would also be required to see if the coupled model exhibits a ‘climate drift’, equivalent to what has been seen in many coupled atmosphere–ocean models.

Modelling the dynamical interactions between the
Fig. 13 Differences in simulated precipitation between interactive vegetation (Years 26–30) and fixed vegetation (Years 6–10) Conditions. Here we compare the difference in precipitation patterns between interactive and fixed vegetation portions of the run. We employ a student $t$-test to assess the statistical significance (at the 95% level) of the differences in precipitation. The significant changes in precipitation are plotted only over land.

physical climate system and the terrestrial biosphere is still in its very early stages. While incremental improvements to both climate and global vegetation models are needed, important methodological issues still need to be resolved. Among these are issues of stability, modes of variability, potential for ‘drift’, sensitivity to initial conditions, as well as the major limitation of coupled models which stems from the computing resources required for long-term simulations. Ideally, a coupled climate-vegetation model would be run over several decades or centuries, which may be more feasible with reduced-form climate models rather than AGCMs (Claussen, pers. comm.). While many of these issues still remain largely unexplored in coupled climate–vegetation models, most of them have been examined by atmosphere–ocean modellers over the last two decades. Atmosphere–biosphere modellers may gain considerable experience from comparing methods with atmosphere–ocean modellers.

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