

# Global climate models and 'dynamic' vegetation changes

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## Abstract

Models of global change must come to incorporate changes in terrestrial vegetation. Here we choose a 1-year meshing (coupling) period to link a global climate model to a well-known biophysical representation of the continental surface by means of eleven vegetation functional types. This coupled model is used to answer two questions: *Can a 'standard' GCM 'cope' with sudden switches in continental characteristics?* and *Does the climate 'care' about the changing underlying vegetation?* We find affirmative answers to both questions. Our results also suggest that those content to generate vegetation *post facto* from climate output have incomplete results.

**Keywords:** vegetation models, coupling to climate, global change, GCM, Holdridge

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## Introduction

In this paper, a pair of experiments is described from which the sensitivity of one global climate model to imposed 'dynamic' changes in vegetational form can be assessed. The timescale chosen is intentionally as short as possible from the point of view of ecological changes (one year). Although this is much too short a timestep to represent, with any verity, ecological changes, it is useful in the context of the half century climate simulations undertaken here. The experiments reported here contribute knowledge at one end of the spectrum of necessary sensitivity assessments. Here we examine the sensitivity of a global climate model to annually imposed changes in vegetational functional form. This sensitivity testing, a necessary first step towards full coupling, employs a methodology analogous to e.g. 'instantaneous' deforestation (e.g. Dickinson & Henderson-Sellers 1988; Nobre *et al.* 1991) or 'instantaneous' doubling of stomatal resistance (e.g. Pollard & Thompson 1994; Henderson-Sellers *et al.* 1995).

Transitions between different biome or ecosystem types are a function of a wide range of processes which operate on many time and space scales. Rapid shifts (< 5 years) generally, of necessity, involve decreases in biomass e.g. severe drought, frost, hurricanes and fire (e.g. Doyle 1981; Noble & Slatyer 1980; Tucker *et al.* 1991). Medium (10–50 years) 'recovery' of forests can be observed in benign environments such as the SE Asia islands and if

human influence is removed. Much longer (50–500 years) ecological succession can be simulated (e.g. Shugart 1984) but at present only by presuming a fixed climate or a prescribed (i.e. known in advance and independently of vegetation changes) changing climate (e.g. Prentice *et al.* 1993). In simulations of future enhanced greenhouse conditions, the climate *cannot* be assumed to be fixed or known in advance nor can human influence be denied (cf. Ojima *et al.* 1994). Thus it must be assumed that rapid as well as longer-term vegetation changes will occur as climate changes. There is a variety of ways of considering the changes in the continental surface characteristics that these vegetation disturbances must imply:

- (a) Ignore them.
- (b) Simulate climate change presuming that vegetation remains fixed and when climate equilibrates generate continental ecology.

Both (a) and (b) *ignore* impacts of vegetation on climate.

- (c) Use results of (b) and continue at equilibrium to achieve a new climate as modified by the new vegetation. Technique (c), which may become an *iterative* process, also assumes that there is a future point at which climate change will stop (presumably at double or triple CO<sub>2</sub>) so that vegetation can 'catch-up'. It ignores shorter-term climatic effects on vegetation due to droughts, frosts and fires and other extreme climate events and their feedbacks.
- (d) Apply a similar vegetation type diagnostic model at intervals during a transient or equilibrating climatic change assuming that this would capture faster ecological changes (i.e. reductions in biomass) but speed-up slower (increasing biomass) changes.

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(e) Employ a 'dynamic' vegetation model globally for long enough for both vegetation and climate to equilibrate (0–500 years).

All published GCM simulations to date have used technique (a). IPCC 2 (Tegart *et al.* 1990) and e.g. Smith *et al.* (1992) and other impact assessors adopted technique (b). A few people have tried (c) (e.g. Claussen 1994). It is assumed that technique (e) is optimum but such 'dynamic' vegetation models, presumably based on the principles underlying succession models, have not yet been created. This use of succession-type models for global simulations of climate and vegetation changes demands recognition of the fact that not only do the climate and the biomes change but also the cause-and-effect relationships between them are subject to change.

With reference to technique (b), we note that Chapter 3 of IPCC 2, entitled 'Natural Terrestrial Ecosystems', devoted one (a two page spread) of its three figures to reproducing the global map of 'changes in climate zones currently associated with specific vegetation' from Leemans (1989). This chapter also comments that estimates of changes in tropical forest areas are 'quite sensitive to scenarios and forest models used' (Tegart *et al.* 1990; p. 3–9) and gives detailed tabulations from Emanuel *et al.* (1985a,b) and Leemans (1989).

Technique (a) is accepted by GCMs – because it is easy(?) – although it ignores vegetation feedbacks. Technique (b) is apparently acceptable to impact modellers although it too ignores vegetation feedbacks. Technique (e) is the goal; (c) and (d) may be steps towards this goal. We explore technique (d) and choose a 1-year meshing (coupling) period.

Any equilibrium scheme is mis-applied when neither predictor nor predictand is in equilibrium, but are climate and ecology *ever* in equilibrium? In the real world, the relationship between vegetation and climate is symbiotic but not exclusive: soils, fauna and human activities all impact vegetation (and climate) (e.g. Riebsame *et al.* 1994). In an idealized globe where only climate and (above ground) vegetation co-exist it is possible to recognize a range of timescales: slow transitions, 'speedy' opportunistic proliferations and die-back, instantaneous windthrow and fire.

It might be more realistic to select a meshing period of 5, 10 or even 50 or 100 years, because some vegetation changes are slow, e.g. forest development or change in forest composition. Elongation of the coupling timestep, in some senses, brings technique (d) closer to technique (c) but also removes shorter time-scale feedbacks of disturbed vegetation on climate which we can explore here. There seems to be no obvious 'best choice' of timescale for coupling although Claussen (1994) has explored some options and concludes that 5 years produces satisfactory results. In the interests of reducing cpu investment

in this preliminary assessment of technique (d), we have chosen to use the shortest possible time period for meshing the continental surface characteristics and the climate: one year.

In this paper we pose, and answer, two closely linked questions: *can a 'standard' GCM 'cope' with sudden switches in continental characteristics?* and *does the climate 'care' about the changing underlying vegetation?* It is clear that time and space scale mismatches are at least as difficult as those between the ocean and atmosphere and between ocean, ice and atmosphere where thermodynamic models can switch sea-ice on and off in 30-minute 'blinks' and 250 000 km<sup>2</sup> clouds 'flicker' on the same time periods. We believe that our use of technique (d) is in line with similar developments in global climate models and especially coupling of subcomponents over the last 15 years. We have not, here, considered changes in the behaviour of vegetation in response to increased atmospheric CO<sub>2</sub> but note that this has been explored elsewhere (e.g. McMurtrie *et al.* 1992; Pollard & Thompson 1994; Henderson-Sellers *et al.* 1995) and could, readily, be linked to the coupling developed here.

### Vegetational functional form

Models of vegetation which could be described as dynamically interactive are currently being designed (USGCRP 1990; B. Walker, personal communication, 1993). It is hoped that a global dynamic vegetation model can be contrived by linking existing landsurface parameterization schemes to ecological models through the mechanism of an agreed description of vegetational functional form. In this study, we examine such a linking using 11 functional vegetation types selected from the 18 usually represented in the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson *et al.* 1986, 1993). These 11 functional vegetation types have been selected based on a number of criteria including (i) their combined success in reproducing plausible vegetation distributions for the present-day climate as simulated by the GCM used here, and (ii) the range of functional characteristics which they represent.

Table 1 lists the 11 functional vegetation types used, together with the 16 parameters which BATS requires in the form of a look-up table in order to fully characterize the continental surface. [Note in these simulations, the soil specification remains constant as originally described by Wilson and Henderson-Sellers, 1985.] The most important characteristics of present-day landsurface parameterization schemes are not yet known, although there have been attempts to rank the vegetation parameters (e.g. Henderson-Sellers 1993a) and there is an international intercomparison under way (Henderson-Sellers & Dickinson 1992; Henderson-Sellers *et al.* 1993). It is generally

**Table 1.** (a) Eleven functional vegetation types, abbreviation and numeric code used when BATS is coupled dynamically into the global model and rankings by roughness length, maximum fractional vegetation and possible seasonal range in vegetation fraction (largest = 1 in each case).

| Functional type              | VFT code | BATS type | Roughness rank | Max. veg fraction rank | Seasonal range in veg. fraction rank |
|------------------------------|----------|-----------|----------------|------------------------|--------------------------------------|
| forest: evergreen broadleaf  | eb       | (6)       | 1              | 1                      | 2                                    |
| forest: deciduous needleleaf | dn       | (4)       | 2              | 5                      | 4                                    |
| tree: deciduous broadleaf    | db       | (5)       | 3.5            | 5                      | 4                                    |
| tree: mixed woodland         | mw       | (18)      | 3.5            | 5                      | 6.5                                  |
| grass: tall (tropical)       | tg       | (7)       | 5.5            | 5                      | 4                                    |
| scrub: semi-desert           | sd       | (11)      | 5.5            | 9                      | 8.5                                  |
| grass: crop/agriculture      | cp       | (1)       | 7              | 2                      | 1                                    |
| scrub: desert                | dt       | (8)       | 8              | 10.5                   | 10.5                                 |
| scrub: tundra                | ta       | (9)       | 9              | 8                      | 6.5                                  |
| grass: short                 | sg       | (2)       | 10             | 5                      | 8.5                                  |
| none: ice cap/glacier        | ig       | (12)      | 11             | 10.5                   | 10.5                                 |

(b) Sixteen parameters associated with the eleven vegetation types employed

| Parameter   | Functional Vegetation Type |      |      |      |      |      |      |      |      |      |      |
|---|----------------------------|------|------|------|------|------|------|------|------|------|------|
|   | cp                         | sg   | dn   | db   | eb   | tg   | dt   | ta   | sd   | ig   | mw   |
| Maximum fractional vegetation cover                         | 0.85                       | 0.80 | 0.80 | 0.80 | 0.90 | 0.80 | 0.0  | 0.60 | 0.10 | 0.0  | 0.80 |
| Maximum fractional vegetation cover range                   | 0.6                        | 0.1  | 0.3  | 0.3  | 0.5  | 0.3  | 0.0  | 0.2  | 0.1  | 0.0  | 0.2  |
| Roughness length (m)  | 0.06                       | 0.02 | 1.0  | 0.8  | 2.0  | 0.1  | 0.05 | 0.04 | 0.1  | 0.01 | 0.8  |
| Depth of the rooting zone soil layer (m)                    | 10                         | 10   | 10   | 10   | 10   | 10   | 10   | 10   | 10   | 10   | 10   |
| Depth of the upper soil layer (m)                           | 0.1                        | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  |
| Fraction of water able to be extracted by upper layer roots | 0.3                        | 0.8  | 0.67 | 0.5  | 0.8  | 0.8  | 0.9  | 0.9  | 0.8  | 0.5  | 0.5  |
| Vegetation albedo for wavelengths < 0.7 µm                  | 0.10                       | 0.10 | 0.05 | 0.08 | 0.04 | 0.08 | 0.20 | 0.09 | 0.17 | 0.80 | 0.06 |
| Vegetation albedo for wavelengths ≥ 0.7 µm                  | 0.30                       | 0.30 | 0.23 | 0.28 | 0.20 | 0.30 | 0.40 | 0.26 | 0.34 | 0.60 | 0.24 |
| Minimum stomatal resistance ( $s\ m^{-1}$ )                 | 120                        | 200  | 200  | 200  | 150  | 200  | 200  | 200  | 200  | 200  | 200  |
| Maximum LAI   | 6                          | 2    | 6    | 6    | 6    | 6    | 0    | 6    | 6    | 0    | 6    |
| Minimum LAI   | 0.5                        | 0.5  | 1.0  | 1.0  | 5.0  | 0.5  | 0.0  | 0.5  | 0.5  | 0.0  | 3.0  |
| Stem (& dead matter) area index                             | 0.5                        | 4.0  | 2.0  | 2.0  | 2.0  | 2.0  | 0.5  | 0.5  | 2.0  | 2.0  | 2.0  |
| Inverse square root of leaf dimension ( $m^{-0.5}$ )        | 10                         | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    |
| Light sensitivity factor ( $m^2 W^{-1}$ )                   | 0.02                       | 0.02 | 0.06 | 0.06 | 0.06 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.06 |
| Zero plane displacement height (m)                          | 0                          | 0    | 9    | 0    | 18   | 0    | 0    | 0    | 0    | 0    | 0    |
| Depth of the vegetation rooting layer (m)                   | 1                          | 1    | 1.5  | 2    | 1.5  | 1    | 1    | 1    | 1    | 1    | 2    |

agreed that roughness length is of considerable importance to the physical exchanges of energy, moisture and momentum between the atmosphere and the continental surface (Henderson-Sellers 1992). Other characteristics of importance in characterizing the vegetation seem likely

to be the leaf area index (LAI), the fractional vegetation cover and perhaps the stomatal resistance. In BATS, as in many 'complex' landsurface parameterization schemes, these physical properties are calculated as a function of ambient and preceding climatic conditions.

Table 1(a) includes rankings for the 11 functional types used here based on the prescribed roughness length, the maximum vegetation fraction permitted and the possible seasonal range in this vegetation fractional cover. It can be seen that ranking on a single characteristic (such as vegetation height) may not produce the same ordering as ranking on fractional vegetation cover (closely related to leaf area index), root distribution (related to the ability to continue to transpire when the upper soil layer has dried) or stomatal resistance. Table 2 shows the way in which the vegetational functional types used here relate to the predictors employed in calculating their year-to-year distribution.

### *The range of models of continental ecology*

It is not clear from the literature how best to characterize the existing 'ecological' models. Heal *et al.* (1993) suggest that there are at least seven groups: leaf, crop, CNPS (biogeochemical), stand, landscape, biophysical and biome (Fig. 1(a)). On the other hand, Malanson (1993) describes only three types: transfer functions, stand models and physiological models. Pacala and Hurtt (1993) argue that stand-type models are likely to be the least successful route by which to estimate future ecological change. In particular, they identify two fundamental problems with the application of stand models such as those of Botkin *et al.* (1972) and Shugart and West (1977): the confusion of fundamental and realized niches and the practice of assuming unlimited dispersal.

There is general recognition that climax/equilibrium models cannot portray any future joint climate and ecological state, for a number of reasons, particularly the human-imposed land-use change and the rate of climate change, forcing disequilibrium. However, it is argued that equilibrium models, while not offering a picture of the future (or past) states can offer some indications of e.g. directions of change and/or possibilities of sustainable land use (e.g. Monserud *et al.* 1993). McGuire *et al.* (1993) use a biogeochemical model, and the assumption of a fixed biome distribution, to provide information about the probably trend in primary production on timescales shorter than those over which biomes respond to altered climate.

The latest description of the plans for coordinated development of a dynamic global vegetation model depends upon the assumption that vegetational functional form, if not the precise nature of the species mix and patch heterogeneity, can be described in terms of fairly simple climatic variables including temperature, precipitation and evaporative demand (e.g. Woodward 1987). Such assertions suggest that these vegetational functional forms could, at least in the case of assumed equilibrium between vegetation and climate, have much

in common with the biome models of Holdridge (1967), Box (1981) and Prentice *et al.* (1992). In these biome models, simple relationships are assumed between climate accumulated over one or more years and the resultant large-scale ecology, e.g. Fig. 1(b) and Table 2. Prentice (personal communication, 1993) plans to accumulate temperature and precipitation over 5-year periods and apply these 'climates' to the BIOME model for palaeoclimatic simulations and Thompson *et al.* (personal communication, 1993) plan to use a 1-year timeframe.

In summary, there exists a range of ecological models which, while not irrelevant to the task of dynamic coupling to global atmospheric models, do not yet fully satisfy all the likely demands.

In this paper, a simple biome model is used to produce classifications of eleven vegetational functional forms which are then used to characterize the information demanded by a biophysical model: BATS.

### **Models used and the experiments**

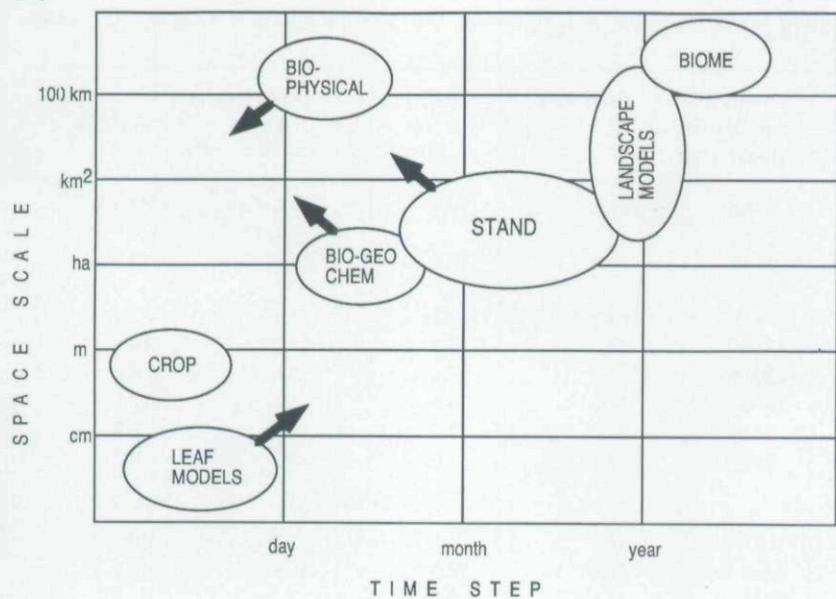
#### *Models*

The global model used here is a version of the NCAR Community Climate Model (CCM), CCM1-Oz, which is integrated at a spatial resolution of about 4.5° latitude by 7.5° longitude (a spectral truncation at rhomboidal wavenumber 15). A full description of CCM1 is given in Williamson *et al.* (1987) and circulation statistics from seasonal and perpetual January and July simulations of the standard version of CCM1 are given in Williamson and Williamson (1987).

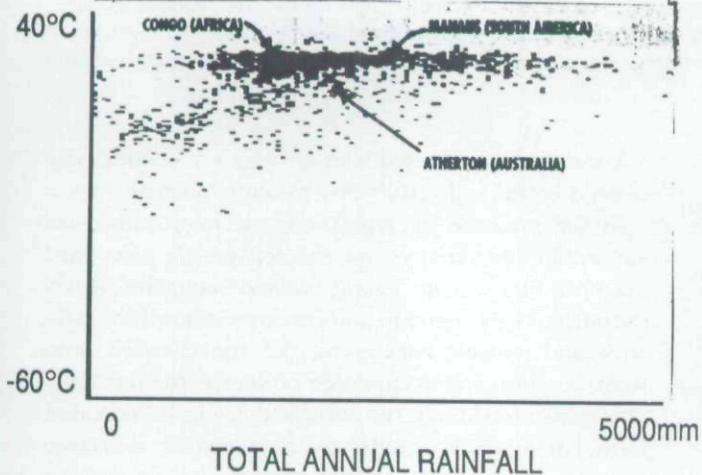
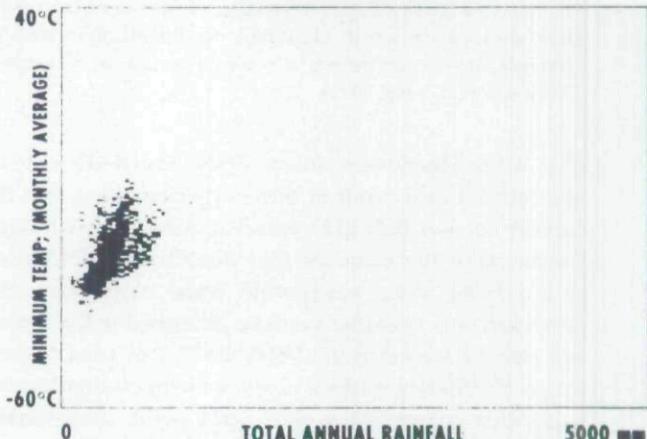
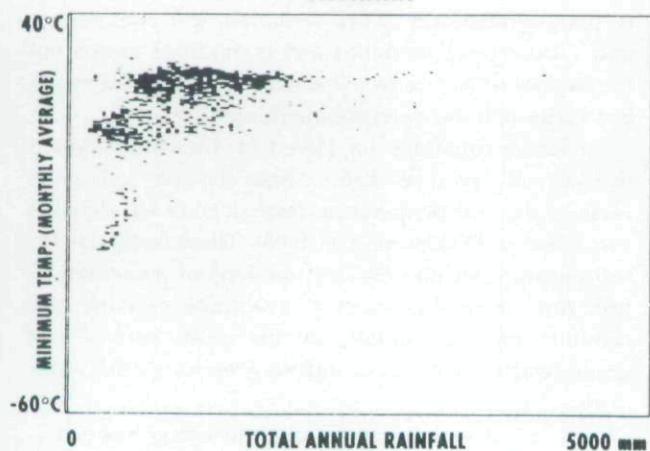
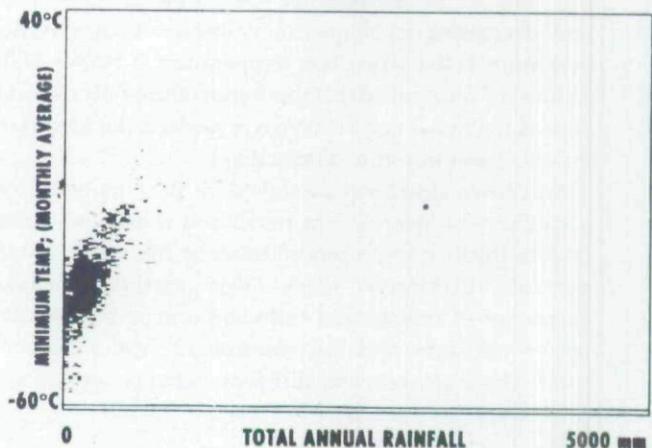
CCM1-Oz is a modified version of CCM1 which includes the current version of the Biosphere–Atmosphere Transfer Scheme (BATS1E) and a mixed-layer, slab ocean of 50 m depth. The mixed layer ocean model includes a three-layer ice model sub-component and a standard q-flux scheme to correct for ocean advection of energy and the prescription of a fixed mixed layer depth. CCM1-Oz includes a number of modifications to the physics subroutines including cloud prediction and radiation updates being tested for the next version of the model: CCM2 (Slingo 1989). The model simulates full seasonal and diurnal cycles and a review of a number of standard global fields shows that the general circulation of the atmosphere is well simulated.

The Biosphere–Atmosphere Transfer Scheme (BATS), first described by Dickinson (1984), incorporates a single vegetation, or canopy, layer, a multiple-layer soil scheme and provision for snow cover on the land-surface. The scheme has been subjected to stability and sensitivity tests both with the NCAR Community Climate Model (e.g. Wilson *et al.* 1987b; Dickinson & Henderson-Sellers 1988) and in off-line mode (e.g. Wilson *et al.* 1987a; Pitman

(a)



(b)

**TROPICAL RAINFOREST****BOREAL FOREST****SAVANNA****TUNDRA**

**Fig. 1** (a) Approximate space and time scales encompassed by the seven types of 'ecological' models identified by Heal *et al.* (1993). In this research we link examples of the two largest-scale model types (a biophysical model and a biome model) to a global climate model. (b) Examples of the global distribution of vegetation types as a function of monthly minimum temperature ( $^{\circ}\text{C}$ ) and annual precipitation (mm) (both modified from Heal *et al.* 1993).

**Table 2.** Percentage areas of the 11 vegetation functional types (VFT) employed here; their limits; associated parameters; % when specified for BATS; % observed; % predicted using 5-year averages of temperature and precipitation 1  $\times$  CO<sub>2</sub> and 2  $\times$  CO<sub>2</sub> (instantaneous) simulations.

| VFT code**            | Limits of predicted VFT*   | Roughness length (cm)/albedo (%) | Prescribed (%)† | Obs <sup>®</sup> 1980 | Predicted(%) 1 $\times$ CO <sub>2</sub> | Predicted(%) 2 $\times$ CO <sub>2</sub> |
|-----------------------|--|----------------------------------|-----------------|-----------------------|---|---|
| cp(1)                 | $T \geq 8, T < 21, P \geq 650, P < 2000$   | 6/10                             | 11.6            | 10.9                  | 14.5                                    | 19.3                                    |
| sg(2)                 | $T \geq 4, T < 6, P \geq 125, P < 300$<br>or $T \geq 4, T < 21, P \geq 300, P < 650$ | 2/10                             | 12.3            | 10.4                  | 14.9                                    | 13.2                                    |
| dn(4)                 | $T \geq 4, T < 8, P \geq 650, P < 2000$<br>or $T \geq 4, T < 6, P \geq 2000$         | 100/5                            | 1.1             | 10.3                  | 13.4                                    | 7.9                                     |
| db(5)                 | $T \geq 21, P \geq 650, P < 2000$  | 80/8                             | 4.0             | 6.3                   | 15.2                                    | 18.8                                    |
| eb(6)                 | $T \geq 21, P \geq 2000$   | 200/4                            | 9.7             | 7.1                   | 8.6                                     | 8.6                                     |
| tg(7)                 | $T \geq 21, P \geq 300, P < 650$   | 10/8                             | 11.0            | 16.9                  | 7.2                                     | 7.7                                     |
| dt(8)                 | $T \geq 21, P < 300$   | 5/20                             | 4.3             | 12.5                  | 6.7                                     | 8.7                                     |
| ta(9)                 | $T < 4$  | 4/9                              | 8.1             | 7.6                   | 3.9                                     | 0.7                                     |
| sd(11)                | $T \geq 4, T < 21, P < 125$<br>or $T \geq 6, T < 21, P < 300,$<br>$P > 125$          | 10/17                            | 10.7            | —                     | 1.2                                     | 0.6                                     |
| ig(12)                | fixed until $T \geq 1.5$   | 1/80                             | 10.6            | 10.5                  | 10.6                                    | 10.2                                    |
| mw(18)                | $T \geq 6, T < 21, P \geq 2000$  | 80/6                             | 4.3             | 5.3                   | 1.2                                     | 1.7                                     |
| Roughness length (cm) |  |                                  | 37.2            | —                     | 46.4                                    | 44.2                                    |
| Shortwave albedo (%)  |  |                                  | 17.0            | —                     | 16.4                                    | 16.5                                    |

\*  $T$  = mean annual biotemperature ( $^{\circ}$ C);  $P$  = total annual precipitation (mm). † from observations as described in Wilson and Henderson-Sellers (1985). <sup>®</sup> Alternative observations for 1980 from Houghton and Skole (1990). \*\* cp = grass: crop/agriculture; sg = grass: short; dn = forest: deciduous needleleaf; db = tree: deciduous broadleaf; eb = forest: evergreen broadleaf; tg = grass: tall (tropical); dt = scrub: desert; ta = scrub: tundra; sd = scrub: semi-desert; ig = none: ice cap or glacier; mw = tree: mixed woodland (Dickinson *et al.* 1986, 1993).

*et al.* 1990; Henderson-Sellers 1994). The BATS scheme has evolved as a result of these experiments so that the current version (BATS1E) which is used here, although substantially the same as that described in Dickinson *et al.* (1986), does incorporate some corrections and improvements to earlier versions described in the literature (see Dickinson *et al.* 1993). BATS can treat a wide range of different surface types, soil characteristics and vegetation covers. At a given grid point, a seasonally dependent fraction of surface covered by vegetation is specified; the remaining fraction is assumed to be covered by bare soil. The fractional vegetation cover varies seasonally based on the assumption of a maximum value when the temperature of the total soil profile is above 298K and decreasing in a quadratic fashion to a specified minimum value when this temperature is below 273K. (It must be recognized that this temperature-only dependence of fractional vegetation cover neglects the important effects of soil moisture availability.)

Prognostic equations are solved for the temperature of a surface soil layer (0.1 m thick) and a deep soil layer (1–2 m thick) using a modification of the force–restore method (Dickinson 1988). This method includes exchanges of radiant and turbulent energy between the upper soil layer and the atmosphere, heat release by water-phase changes and diffusion between the top and

lower soil layers. The soil heat capacity and conductivity depend on the soil texture and moisture content.

In the presence of vegetation, the temperatures of air within the canopy and the foliage are calculated diagnostically via an energy balance equation which includes canopy–ground and canopy–atmosphere radiative and sensible heat exchanges, transpiration from stomatal pores and evaporation of intercepted moisture. The transpiration rate is calculated using a resistance formulation which includes the aerodynamic resistance to fluxes of moisture and heat from the foliage and the mechanical resistance encountered by the diffusion of moisture from inside a leaf to outside (or stomatal resistance). The stomatal resistance depends on the flux of photosynthetically active radiation, leaf temperature and vapour pressure deficit and is modified to account for the root resistance to soil water uptake by the canopy but varies only between specified limits.

Predictive equations are solved for the water content in three soil layers as distinct from the two soil layers used in the soil temperature formulations (cf. detailed discussion in Dickinson *et al.* 1993). These equations for soil moisture include the contributions of precipitation, leaf drip from the canopy, evapotranspiration and resulting moisture uptake by the roots, surface and groundwater runoff and diffusive exchange of water

between soil layers (Dickinson 1984). Root uptake of moisture can only occur from the upper two soil layers which correspond to the two layers used in the soil temperature formulation.

The scheme incorporates snow, frozen soil water and related phase changes. A prognostic equation including precipitation, sublimation and snow melt is solved for the snow depth for each grid point. The fractional snow cover is calculated diagnostically from the average snow depth at the grid point and the roughness length of vegetation or bare soil (see Dickinson *et al.* 1986, 1993).

For each vegetation type, vegetation albedos are specified for the ultraviolet/visible and near-infrared regions of the solar spectrum. The albedo for bare soil depends on soil colour class and decreases with soil water content. It varies from 0.05 to 0.2 in the ultraviolet/visible region and from 0.1 to 0.4 in the near-infrared region. The albedos for diffuse radiation are assumed to be the same as those for direct radiation. At a given grid point, the surface albedo is obtained by averaging over vegetated, bare soil and snow-covered areas. The BATS code also includes a calculation of net carbon gain or loss by the vegetation and soil systems due to photosynthesis, respiration and decay although the photosynthetic calculation is, at present, highly simplified.

Sensible heat, water vapour and momentum fluxes at the surface are calculated from a standard surface drag coefficient parameterization. The drag coefficient for a given grid point is obtained via an average over vegetated, bare soil and snow-covered areas. The drag coefficients are expressed as a neutral drag coefficient times an atmospheric stability correction factor. The neutral drag coefficient is a logarithmic function of the height of the bottom atmospheric model level and the specified roughness length of vegetation, bare soil, water or snow. The stability correction factor is assumed to be the same for momentum, heat and water vapour transfer and is expressed in terms of the local bulk Richardson number. In order to use this drag coefficient parameterization, the bottom atmospheric level in the host model should not exceed a few tens of metres.

When coupled to a meteorological or climate 'host' model, the vegetation type, soil texture and soil colour need to be specified for each grid point, along with the initial snow cover, soil moisture and ground and foliage temperatures. From the host model then, BATS requires as input the ambient meteorology such as temperature, humidity and surface radiant fluxes. From these and other internally generated quantities, BATS calculates temperatures of the surface soil, deep soil, canopy foliage and canopy air, the soil moisture in three layers, snow cover and surface fluxes of momentum, heat and moisture. The surface fluxes are then fed into the momentum, thermodynamics and water vapour equations of the host

model as lower boundary conditions. The continental surface climate, upon which the vegetation prediction scheme used here is a function, is critically dependent upon these fluxes which are, in turn, dependent upon the characteristics and parameterizations in BATS.

### Coupling

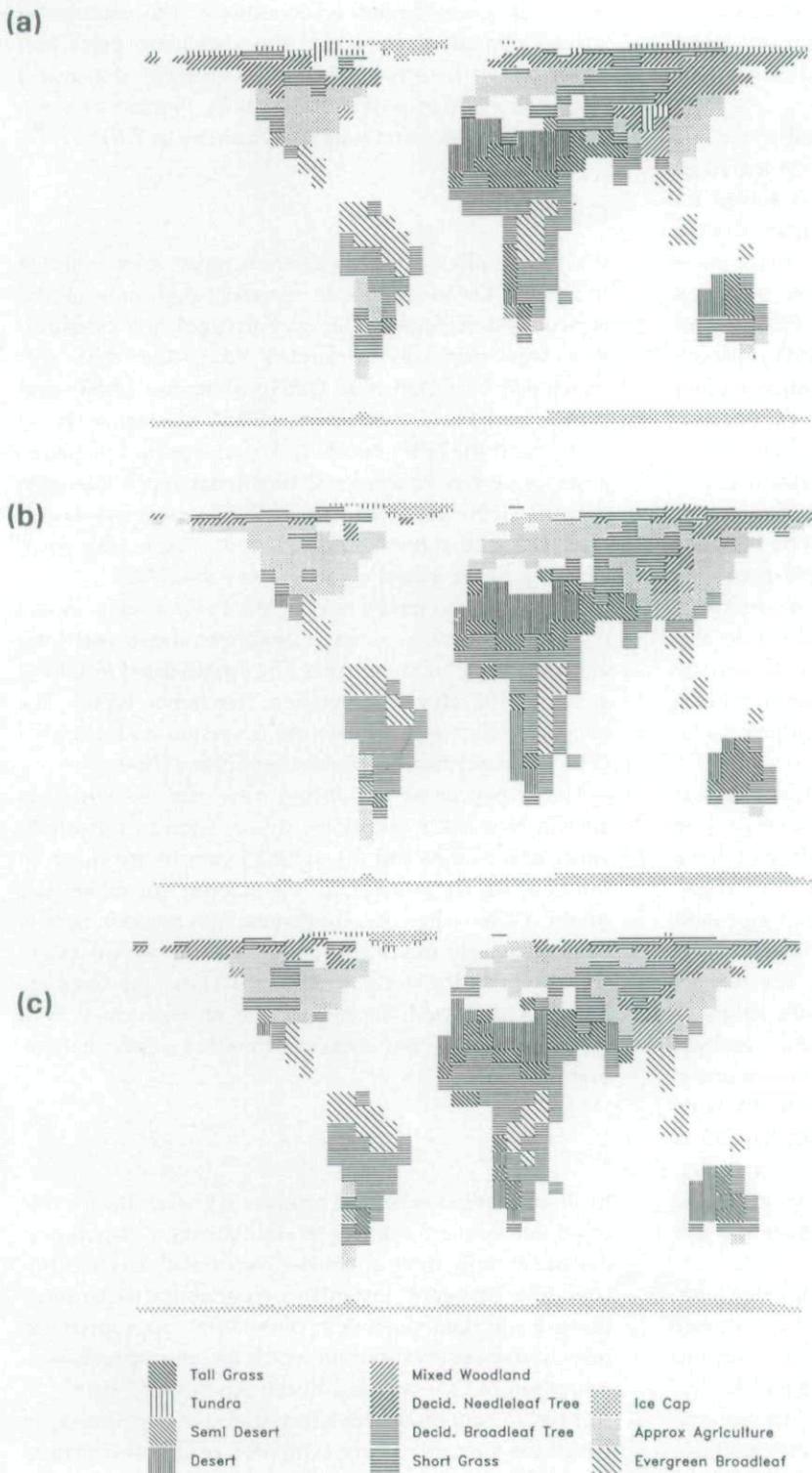
BATS normally uses 18 vegetation types when coupled to CCM1-Oz to attempt to represent both natural and agricultural ecologies. This global vegetation classification was originally generated from the data sets developed by Olson *et al.* (1983), Matthews (1983), and Wilson and Henderson-Sellers (1985); the former being  $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$  and the latter two  $1^\circ \times 1^\circ$  archives. In this paper, a set of eleven vegetational functional types has been derived (Table 1a). There are sixteen parameters associated with each of these functional types (Table 1b) when coupling to the global climate model via BATS.

The vegetation model is 'coupled' to the climate model by use of annually average biotemperatures and total annual precipitation amounts. The ranges listed in Table 2 generate the eleven vegetation functional types. The coupling scheme is, in essence, a version of Holdridge (1967) as described by Henderson-Sellers (1993b).

The experiments conducted here are designed to answer two linked questions: (i) a numerical sensitivity study of the GCM and (ii) a climatic sensitivity study. In the first, we try to ascertain the stability (or otherwise) of the GCM when its continental lower boundary is instantaneously modified and, in the second, we assess the impact on the simulated climate. These questions are intrinsically linked. Moreover, the answers may well be a function of the coupling timestep selected: here, one year.

### Experiments

In all, six experiments were conducted to examine the role of an interactive biosphere in simulations of the climate system. Initially, three doubled-CO<sub>2</sub> simulations were utilized: (i) a 'standard' instantaneous doubling experiment using a specified vegetation distribution appropriate to present day observations, in which the atmospheric concentration of CO<sub>2</sub> is raised to 660 p.p.m.v and the GCM allowed to equilibrate; (ii) a fast, transient experiment, in which the atmospheric concentration of CO<sub>2</sub> is increased gradually over 35 years until the amount has doubled and then the climate model is allowed to equilibrate with this CO<sub>2</sub> level held constant; and (iii) a doubled CO<sub>2</sub> experiment with prescribed vegetation cover (fixed at present-day distributions) and continued from the end of case (i). In addition, a control (fixed vegetation) and interactive vegetation for  $1 \times \text{CO}_2$  experiments were performed. The



**Fig. 2** (a) Vegetation functional types' distribution predicted, off-line, from ensemble means of biotemperature and precipitation from 5-years of the  $1 \times \text{CO}_2$  control climate. (b) Vegetation functional types predicted at the end of the last year (year 15) of the instantaneous doubled  $\text{CO}_2$  simulation. (c) As for (b) except from the last year (year 45) of the fast, transient doubled  $\text{CO}_2$  simulation.

fast, transient, doubling uses a 2% per annum compound rate of increase justifiable (Houghton *et al.* 1990, 1992; Policy Makers Summary 1990; Houghton 1991) if recent estimates of projected emissions are taken into account. The

transient experiment permitted an evaluation of the final impact on climate of different rates of vegetation change (slower in the transient than in the instantaneously doubled  $\text{CO}_2$  experiment).

### Assessing the sensitivity of a global model to 'responsive' vegetation

#### A coupled vegetation-climate model

Figure 2 compares the distributions of vegetational functional types derived for  $1 \times \text{CO}_2$  (Fig. 2a), at the end of the instantaneous  $2 \times \text{CO}_2$  simulation (Fig. 2b) and at the end of the transient  $\text{CO}_2$  simulation (Fig. 2c). Note there is a considerable increase in the area predicted as being appropriate for agriculture (VFT cp) whereas the total area of tropical forest (VFT eb), itself a contributor to atmospheric  $\text{CO}_2$ , changes very little (Table 2). Comparing the response of the vegetation to instantaneous doubling to that produced during a fast, transient doubling experiment shows similar trends in vegetation distribution, but the instantaneous doubling results in a greater area of 'crop' at the expense of deciduous needleleaf tree (VFT dn). However, the results of this interactive evaluation of terrestrial vegetation distribution and dynamics in a warming world must be treated with considerable caution; in particular because there is no  $\text{CO}_2$  fertilization effect on the predicted vegetation distribution. At the minimum, however, the vegetation functional types 'prediction' scheme delineates climate zones hospitable to the identified vegetation types. The general impact of climate on vegetation is similar to earlier studies (e.g. Emanuel *et al.* 1985a,b; Leemans 1989).

More interestingly, these experiments also allowed investigation of whether changes in vegetation form affect the GCM's simulated climate. The strongest signal might be expected to be in the land-surface climate parameters. Indeed, Henderson-Sellers (1993b) found that the introduction of the interactive biosphere for a present-day simulation resulted in an increase in evaporation of up to  $5 \text{ W m}^{-2}$  over the continental surface and increases in absorbed solar radiation and surface temperature (up to  $1.5^\circ\text{C}$ ). Figure 3 shows the evaporation over the continental surfaces for the 5 years of two paired sets of model runs at  $1 \times \text{CO}_2$  and  $2 \times \text{CO}_2$ . In each case, the simulation which incorporates an interactive vegetation scheme gives rise to increased evaporation over the continents which is particularly marked in northern hemisphere summer (July is month 7, 19, etc.).

Table 3 summarizes some climate statistics resulting from the three  $2 \times \text{CO}_2$  experiments as differences from, or percentages, the  $1 \times \text{CO}_2$  control. The rootzone soil moisture appears to be sensitive to the inclusion of an interactive biosphere but this response is, in part, the result of changes in rootzone soil depth which is itself a function of the vegetation functional type. There is almost no difference in this variable between  $1 \times$  and  $2 \times \text{CO}_2$  when the BATS-prescribed vegetation is used. Planetary albedo decreases as in most doubled- $\text{CO}_2$  experiments,

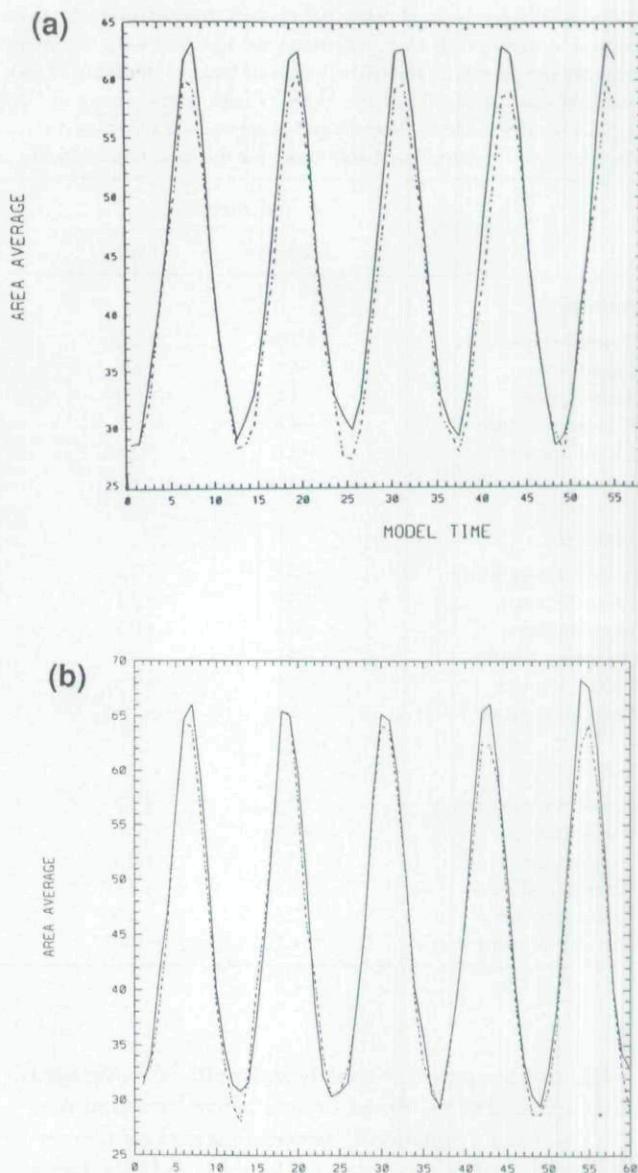


Fig. 3 (a) 5-year time series of evaporative flux ( $\text{W m}^{-2}$ ) over the continents only for  $1 \times \text{CO}_2$  with fixed vegetation (dash) and interactive vegetation (solid). (b) as (a) except for  $2 \times \text{CO}_2$  (equilibrated after instantaneous doubling).

partly as a result of decreased cloud amount and partly because of the ice-albedo feedback. Here, a small component of the decrease in planetary albedo over the land is the result of the decrease in ice-cap area (Fig. 2) which can be modified to one of the other vegetational functional types if climate warms. The sea-ice area is found to be sensitive to both the inclusion of an interactive biosphere and the mode of  $\text{CO}_2$  increase, the sea-ice area remaining larger (i.e. the smallest decrease) in the case of the transiently increasing  $\text{CO}_2$ .

**Table 3** Differences in climatic parameters derived from the three doubled CO<sub>2</sub> simulations (5-year ensemble means), the 1 × CO<sub>2</sub> control integration (i) after instantaneous doubling with the interactive vegetation; (ii) after a fast, transient doubling of CO<sub>2</sub> with the interactive vegetation and (iii) after instantaneous doubling of CO<sub>2</sub> but reverting to the present-day prescribed vegetation. In all cases, the land area is 34.17% of the globe. Screen temperatures are differences in Kelvin and all other parameters are given as % of the 1 × CO<sub>2</sub> values. Cloud amount and rootzone soil moisture are for 00Z only, all other values are diurnal averages. Sea-ice is given for the globe and rootzone and soil water for the land entries in the lowest rows.

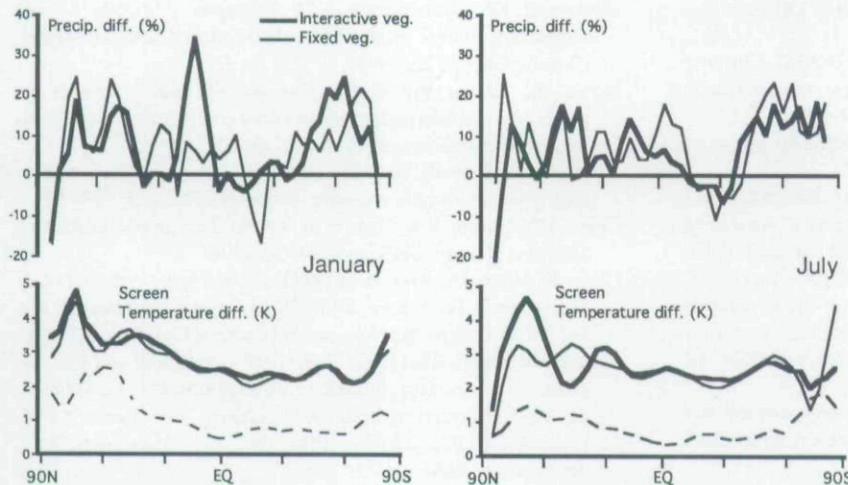
|                        | Instantaneous |       | Fast, transient |       | Constant vegetation |      |
|------------------------|---------------|-------|-----------------|-------|---------------------|------|
|                        | Globe         | Land  | Globe           | Land  | Globe               | Land |
| <b>Annual</b>          |               |       |                 |       |                     |      |
| Screen temperature     | +2.5          | +3.0  | +2.5            | +2.9  | +2.5                | +3.0 |
| Precipitation          | +6.1          | +6.1  | +6.0            | +7.1  | +5.6                | +5.2 |
| Evaporation            | +6.1          | +8.4  | +6.0            | +8.8  | +5.6                | +5.7 |
| Planetary albedo       | -4.6          | -3.7  | -4.3            | -3.7  | -4.3                | -3.4 |
| Cloud amount           | -2.6          | -2.6  | -2.2            | -1.9  | -2.4                | -2.1 |
| Sea-ice/rootzone water | -41.8         | -16.9 | -37.5           | -16.8 | -39.8               | -2.1 |
| <b>January</b>         |               |       |                 |       |                     |      |
| Screen temperature     | +2.7          | +3.4  | +2.6            | +3.5  | +2.7                | +3.4 |
| Precipitation          | +5.5          | +3.1  | +5.8            | +8.6  | +5.6                | +3.6 |
| Evaporation            | +5.3          | +8.9  | +5.8            | +13.2 | +5.5                | +4.9 |
| Planetary albedo       | -4.6          | -4.1  | -4.3            | -4.1  | -4.6                | -4.3 |
| Cloud amount           | -2.8          | -2.8  | -2.6            | -1.8  | -2.6                | -3.5 |
| Sea-ice/rootzone water | -55.4         | -17.4 | -46.1           | -15.8 | -54.0               | -1.6 |
| <b>July</b>            |               |       |                 |       |                     |      |
| Screen temperature     | +2.5          | +2.7  | +2.3            | +2.5  | +2.4                | +2.7 |
| Precipitation          | +5.8          | +4.6  | +6.7            | +9.2  | +5.7                | +5.7 |
| Evaporation            | +5.8          | +7.5  | +6.9            | +8.4  | +5.8                | +4.7 |
| Planetary albedo       | -4.2          | -3.5  | -3.5            | -3.2  | -3.8                | -3.5 |
| Cloud amount           | -2.8          | -3.0  | -2.2            | -1.2  | -2.0                | -2.1 |
| Sea-ice/rootzone water | -41.2         | -17.7 | -39.9           | -18.0 | -41.0               | -2.9 |

Figure 4 compares the zonally and multi-year averaged differences [2 × CO<sub>2</sub> (fixed or interactive vegetation) – 1 × CO<sub>2</sub> (fixed vegetation)], Stevenson screen air temperature and total precipitation for January and July. Large temperature differences are seen in July in high latitude locations where sea-ice differences occur whereas tropical precipitation is sensitive to the incorporation of interactive vegetation. In common with most simulations of greenhouse climates, the temperature change signals are statistically significant (the lowest curves on the temperature graphs in Fig. 4 are of one standard deviation) while the precipitation changes are generally not significant. On the other hand, the differences between fixed and interactive vegetation simulations are always smaller than the model's natural variability (cf. Fig. 3).

The evaporation from the continents is noticeably larger when the vegetation is interactive than when it is prescribed at the present-day distribution and, in the annual mean, the global (oceans as well as land) evaporation is greater when the vegetation is interactive (Table 3). Preliminary analysis indicates that the vegetation changes may

be prompting a feedback between the atmosphere and the oceans, via low-level convergence changes, which further increases global evaporative flux. Specifically, including the interactive biosphere in both 1 × and 2 × CO<sub>2</sub> simulations tends to enhance the Hadley circulation.

Doubling of CO<sub>2</sub> (without any change at the landsurface) results in a weaker winter branch (decreases between the equator and 35°) but a slightly stronger summer branch (increases from the equator to 35°) indicating enhanced circulation. The presence of an interactive biosphere produces similar changes in the meridional circulation. The winter branch of the Hadley circulation is diminished and the summer branch is enhanced. Differences at higher latitudes are much smaller and harder to identify clearly. Changes in meridional circulation induced by allowing the biosphere to respond to the climate are similar in character and of the same magnitude as changes induced by doubled CO<sub>2</sub>. In both cases, there is stronger low-level flow over summertime tropical oceans which has the potential to operate as a positive feedback by increasing evaporation.



**Fig. 4** January and July differences ( $2 \times \text{CO}_2 - 1 \times \text{CO}_2$ ) in zonally averaged (land, ocean and sea-ice) screen temperature (K), total precipitation (% of  $1 \times \text{CO}_2$ ) with interactive and fixed continental vegetation. All differences are with a  $1 \times \text{CO}_2$  simulation with fixed vegetation. For screen temperature, one standard deviation of the  $1 \times \text{CO}_2$  (control) values is also shown (lowest curve).

## Summary

It is doubtful whether vegetation and climate are ever in equilibrium. Certainly, these experiments, which couple a very simple (eleven class) representation of vegetation functional form to a fairly standard global climate model, show feedbacks operating in both directions: the climate alters the vegetational form and changing vegetation modifies the climate.

In this paper we pose, and answer, two questions:

### 1 Can a 'standard' GCM 'cope' with sudden switches in continental characteristics?

In our study, these are annual but even when the supposedly 'correct' succession models are developed and applied, the 'switches' will still have to be imposed. This result is likely to hold even if, later, the timescale of coupling is changed (cf. Claussen 1994).

### 2 Does the climate 'care' about the changing underlying vegetation?

We conclude that an interactive vegetation does modify the climatic change due to doubling of atmospheric  $\text{CO}_2$ . The most direct changes are enhanced continental evaporation which prompts intensification of the atmospheric circulation in the tropics and, in turn, enhanced oceanic evaporation. This second affirmative answer is a more trying result for those content to generate vegetation *post facto*. At a minimum, it means their diagnosis is incomplete since their analysis neglects feedbacks between climate and vegetation. Probably it also means that coupling vegetation and climate is to become just as contentious as coupling ocean and atmosphere.

There is no one, simple solution to the 'best means' of coupling models of terrestrial vegetation into global climate models. Sensitivity studies of the types described here are essential first steps towards 'dynamic' modelling of global change.

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