

On multiple solutions of the atmosphere–vegetation system in present-day climate

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Abstract

An asynchronously coupled global atmosphere–biome model is used to assess the stability of the atmosphere–vegetation system under present-day conditions of solar irradiation and sea-surface temperatures. When initialized with different land-surface conditions (1, the continents, except for regions of inland ice, completely covered with forest; 2, with grassland; 3, with (dark) desert; and 4, with (bright) sand desert), the atmosphere–biome model finds two equilibrium solutions: the first solution yields the present-day distribution of subtropical deserts, the second reveals a moister climate in North Africa and Central East Asia and thereby a northward shift of vegetation particularly in the south-western Sahara. The first solution is obtained with initial condition 4, and the second with 1, 2, 3. When comparing these results with an earlier study of biogeophysical feedback in the African and Asian monsoon area, it can be concluded that North Africa is probably the region on Earth which is most sensitive considering bifurcations of the atmosphere–vegetation system at the global scale.

Keywords: atmosphere–biome interaction, biogeophysical feedback, biome modelling, global atmosphere–biome system

Introduction

Traditionally, vegetation has been considered as a passive component of climate (e.g. Köppen 1936 who considers vegetation as ‘crystallized, visible climate’). At the same time, it is recognized that vegetation can play an active role in the climate system by amplifying climate changes induced by, for instance, changes in the Earth’s orbit (e.g. Foley *et al.* 1994; deNoblet *et al.* 1996; Kutzbach *et al.* 1996; Claussen & Gayler 1997). Although the climate system consists of many subsystems (not just the atmosphere) it seems worthwhile to isolate mechanisms and to explore the feedbacks between the atmosphere and the vegetation by coupled atmosphere–vegetation models. First attempts in this direction were undertaken by Henderson-Sellers (1993) and Claussen (1994).

In the latter paper, it is mentioned that the atmosphere–vegetation system could be an intransitive system, as the coupled atmosphere–vegetation model yields different solutions depending on the initial conditions. An example of such intransitive behaviour is given by Claussen (1997) who assesses the problem of the dynamics of deserts and drought in the African and Indian Monsoon region, i.e. Sahel, Saudi-Arabia, and the Indian subcontinent. It is found that – under present-day conditions of solar

irradiation and sea-surface temperatures (SST) – two solutions of the atmosphere–vegetation system, or more precisely the atmosphere–biome system¹, are possible: the first solution yields the present-day distribution of vegetation and deserts and the second one shows a northward spread of savanna and xerophytic shrub of some 600 km, particularly in the south-western Sahara. Whether the atmosphere–biome model would attain the first or the second solution depends on the initial conditions. If a bright sand desert (i.e. a desert with a high albedo of some 35%) is prescribed in the area currently occupied by the Sahara desert, then the atmosphere–biome model keeps the desert. If, however, vegetation is initially specified, then some vegetation (savanna, xerophytic shrub, and steppe) remains in the south-western Sahara.

The study of Claussen (1997) focuses on biogeophysical feedback in the tropical and subtropical regions. Vegetation patterns are changed only in these regions. The only initial conditions considered are subtropical deserts as they exist today, and subtropical deserts replaced by forest and tropical forests by desert. Here, this regional study is extended to a global scale. It is explored whether

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¹A biome is defined as a macro ecosystem being in equilibrium with climate.

there are more than two solutions of the atmosphere–biome system when considering the entire globe. It is tested whether there are other regions than the Sahara – Arabian – Indian deserts in which multiple solutions of the atmosphere–vegetation system emerge. For example, it is investigated whether the so-called forest-snow-albedo feedback² will lead to multiple solutions in the boreal regions. Therefore, the range of solutions of an atmosphere–biome model – described in the following section – is explored by comparing various simulations which are started from globally different initial conditions.

The atmosphere – biome model

The atmospheric component

As the atmospheric component of the combined atmosphere–biome model, the climate model ECHAM (version 3.2) is taken, which was developed at the Max-Planck-Institut für Meteorologie in Hamburg (see Roeckner *et al.* 1992). In this study, ECHAM is run at T21 resolution, hence the Gaussian grid has a resolution of some $5.6^\circ \times 5.6^\circ$ longitude/latitude.

Computation of near-surface transfer of energy, moisture and momentum is based upon the Monin-Obukhov theory as formulated by Louis (1979). Soil moisture is predicted using the bucket-type Arno scheme of Dümenil & Todini (1992), and evaporation using the Blondin (1989) scheme. The latter scheme takes into account vegetation effects such as interception of rain and snow in the canopy and the stomatal control of evaporation in a grossly simplified manner. The albedo of snow-covered surfaces depends on the type of vegetation. While the albedo of snow-covered bare soil and grassland can reach from 0.4 to 0.8, depending on temperature, it is restricted to 0.3–0.4 in the case of snow-covered forests. The surface parameters, i.e. the parameters which are defined to control energy and momentum fluxes at the atmosphere – surface interface, such as background albedo, roughness length, vegetation ratio and forest ratio (relative area of a grid cell covered by vegetation and forest, respectively), and leaf area index (area of leaves covering 1 m² surface area), are taken as constant with respect to time depending only on the biome type (see section on Coupling of the atmospheric and biome components).

ECHAM is able to simulate the present-day observed time-mean circulation and its intraseasonal variability. Particularly the simulated global distributions of near-

surface temperature and precipitation agree well with observations. Differences between simulated and observed temperatures are generally smaller than $\pm 1^\circ\text{C}$ on seasonal average. Exceptions are a cold bias of some -2°C in the NW of North America, the central Sahara, and Siberia during the summer months (June, July, August) and a cold bias of -4°C in Siberia during winter (December, January, February). Concerning precipitation, the structure of the tropical belt is well captured, as are the storm track regions of the Northern Hemisphere. Deviations from observed patterns are found for South Africa and Australia which receive too much rain during the southern summer (December, January, February). Moreover, the dry regions with a precipitation rate of less than 0.5 mm d^{-1} are more extended than the Legates & Willmott (1990) analysis suggests. For an extensive report, reference is made to Roeckner *et al.* (1992), Arpe *et al.* (1994) and Bengtsson (1994). How these regional deficiencies in the ECHAM simulation affect the prediction of biome patterns will be discussed in the following section.

The biome component

Biomes are computed by using the BIOME model (version 1.0) developed by Prentice *et al.* (1992). This model is based on physiological considerations rather than on mere correlations between climate and biomes as they exist today. Therefore, the BIOME model is suitable as a tool to assess changes in natural vegetation in response to changes in climate. However, it is important to note that the BIOME model does not simulate the transient behaviour of vegetation. At best, it predicts constraints within which plant community dynamics could operate.

In the BIOME model, 14 plant functional types are assigned climate tolerances in terms of amplitude and seasonality of climate variables such as coldest monthly mean temperature, yearly temperature sums, and ratio of actual to equilibrium evapotranspiration. Competition between different plant types is treated indirectly by the application of a dominance hierarchy which effectively excludes certain types of plants from a site based on the presence of other types rather than because of climate. Finally, the biomes are defined as combinations of dominant types.

Here, we use a slightly modified version of the BIOME model. Instead of defining 17 biomes, as in the original model, we specify only four biome groups: forest, grassland, desert, and sand desert (see Table 1). Sand desert is not included in the original version of BIOME, but its definition will be discussed in the following section. Biomes have been collected into biome groups because the difference in surface parameters allocated to biomes (see following section) are significant only between these

²Snow-covered forests appear to be darker than snow-covered grassland. Hence a change in vegetation could alter the radiation budget in boreal regions (e.g. Foley *et al.*, 1994; de Noblet *et al.*, 1996).

four biome groups, but small among the original biomes within each group.

In Fig. 1(a–b), biome groups diagnosed from observed and computed climatologies are depicted. Climate data are taken from Leemans & Cramer (1991), and model results from a 30-year run of ECHAM-3.2. It is evident that the global biome patterns computed from ECHAM climatology agree fairly well with those derived from data – corroborating the ability of ECHAM to recapture the global distribution of precipitation and near-surface temperature. The global κ value is 0.49. (The Kappa

statistics are presented by Monserud & Leemans, 1992, as an objective tool for comparing global vegetation maps. κ values range from 0 to 1; the smaller the number, the worse the agreement.) Differences between biome maps reflect the above-mentioned regional deficiencies of ECHAM. Too much forest is diagnosed from the ECHAM simulation for Australia. In boreal latitudes, there appears to be a lack of taiga and tundra due to the cold bias of the ECHAM simulation.

Table 1 Allocation of biomes defined by Prentice *et al.* (1992) to biome groups used in this study

biome	biome group
tropical rain forest	forest
tropical seasonal forest	
savanna	
warm mixed forest	
temperate deciduous forest	
cool mixed forest	
cool conifer forest	
taiga	
cold mixed forest	
cold deciduous forest	
xerophytic woods/shrub	grassland
warm grass/shrub	
cool grass/shrub	
tundra	
hot desert	desert
cool desert	
polar desert	
(new type)	sand desert)

Coupling of the atmospheric and biome components

ECHAM is asynchronously coupled with the BIOME model: from climate variables computed by ECHAM, biome groups are diagnosed by using the BIOME model. Subsequently, surface parameters are allocated to biome groups. With the new surface parameters the simulation with ECHAM is continued for some model years – based on earlier investigations (Claussen 1994), six years are chosen from which the first year is omitted as an adjustment period for soil-water transports. From the new simulation biomes are diagnosed again and so on. The sequence of allocation of surface parameters to biome groups, integration with ECHAM, and computation of biomes using the BIOME model is referred to as ‘iteration’. Several interactions are performed until the biome patterns and the state of the atmosphere no longer reveal any significant trend.

Allocation of surface parameters to biome groups is mainly based on the experience gained in earlier studies. Surface parameters allocated to individual biomes, as described in Claussen (1994, 1997), are averaged and weighted with the biome area to yield the surface para-

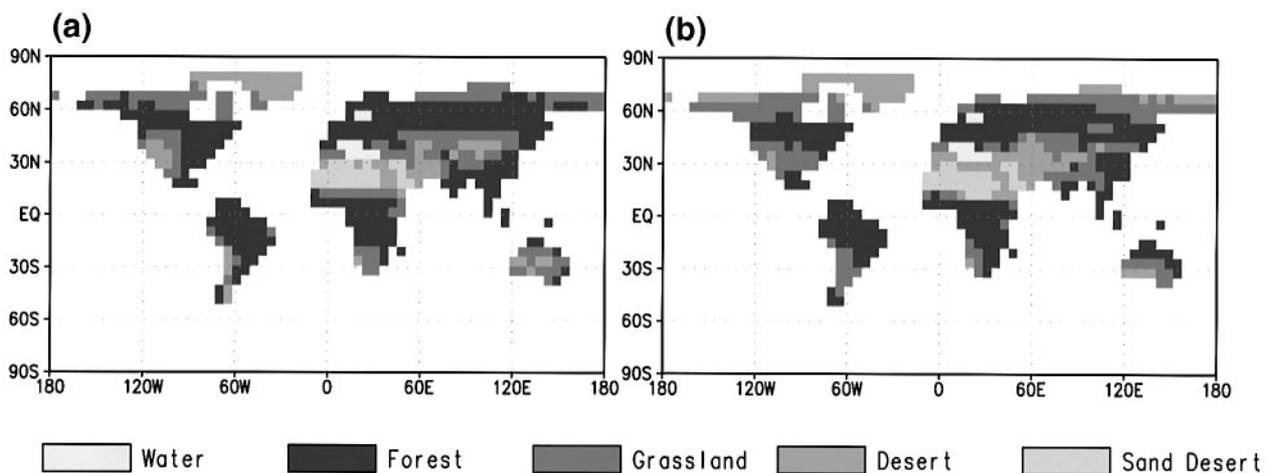


Fig. 1 Biome patterns computed (a) from climate data by Leemans & Cramer (1991) and (b) from a 30-year simulation of present-day climate using the atmospheric general circulation model ECHAM-3. Black patches indicate forest; dark gray patches, grassland; grey patches, desert; and light grey patches, sand desert.

Table 2 Allocation of the surface parameters background albedo α , leaf area index LAI, vegetation ratio c_v , forest ratio c_F , and roughness length z_{ov} to biome groups

	biome group	α	LAI	c_v	c_F	z_{ov} [m]
1	forest	0.14	6.0	0.9	0.75	0.700
2	grassland	0.18	2.0	0.6	0.05	0.050
3	desert	0.20	0.5	0.2	0.00	0.003
4	sand desert	0.35	0.0	0.0	0.00	0.003

meter of biome groups. The results are given in Table 2. Of course, there are differences in surface parameters within a biome group. For example tropical rain forest, savanna, and taiga certainly differ in leaf area index and stomatal physiology. However, in an initial study like this one, which focuses on gross surface changes, these differences are neglected.

In Claussen (1997) the biome 'sand desert', which is not included in the original BIOME model, was introduced to take into account the large differences between albedo values of various types of desert. In the Sahara and Arabian deserts, large patches of high albedo – in some places up to 0.42 – are observed by satellite (e.g. Ramanathan *et al.* 1989). Therefore, whenever the BIOME model predicts a desert biome in these regions, 'sand desert' was chosen.

Here, sand desert is supposed to be a function of soil moisture availability (i.e. the ratio of actual to equilibrium evapotranspiration) and surface topography. From correlations of albedo observations (Ramanathan *et al.* 1989) with climate simulations it is found that sand desert can appear whenever the soil moisture availability falls below a value of 0.05. Moreover, it is found that the region in which sand deserts occur must be rather smooth, i.e. the roughness length should not exceed 2.0 m on average of the grid cell. Furthermore, the water surface (which is a surface of very low albedo) should not cover more than 10% of a grid cell. Hence in this study sand desert is computed from this (*ad hoc*) scheme rather than prescribed by using a sand desert mask specified from satellite data.

The experiment

To assess the problem of multiple solutions of the atmosphere–biome system, four experiments are set up, each of which is initialized with the land surface, except for regions of inland ice, completely covered by just one biome group. In this way it should be possible to scan the entire range of solutions of the ECHAM-BIOME model. Small deviations in initial conditions generally do not yield different solutions, as found by Claussen (1994). The experiments are labelled Exp1 in the case of continents initially covered by forest only, Exp2 when

land is covered by grassland, Exp3 by desert, and Exp4 by sand desert.

For each initial condition, nine iterations, i.e. 54 simulated years in total, are performed. The area covered by each biome group as a function of the Figiteration steps is shown in Fig. 2(a–d). With the initial surface conditions, ECHAM is run for 12 years. The biomes computed from the years 2–6 are not fed into ECHAM. Hence the first iteration is done 'off-line'. The iteration continues with biomes from years 8–12. This procedure is undertaken just to check whether ECHAM has adapted to the rather anomalous initial land-surface conditions. As seen in Fig. 2(a–d) (and also in the biome maps which are not shown here), the differences between the first ('off-line') and second iterations are small. This indicates that the near-surface climate has adapted to the initial conditions. Moreover, it corroborates the supposition that a simulation time of six years should be sufficient for each iteration.

Results

Global perspective of biome patterns

The iteration series of the areal coverage of biome groups are analysed for positive or negative trends. It is found that there is no significant trend (at a significance level of 95%) over the last 7 iterations in Exp1. In Exp2 and Exp4, the series of the last 4 iterations does not exhibit any trend, and in Exp3, the series of the last 6 iterations.

The climate variables relevant for the BIOME model (i.e. temperature of coldest month, yearly temperature sums, annual soil moisture availability) on average over the iterations of the trend-free part of the series are used to construct the biome patterns depicted in Fig. 3(a–d). Inspection of Fig. 3(a–d) suggests that the ECHAM-BIOME model finds basically two solutions which resemble those given earlier by Claussen (1997): Exp1, Exp2, and Exp3 yield a small Sahara desert, whereas the Sahara desert in Exp4 is much larger – by and large occupying its present-day area. The global κ values corroborate the visual impression: κ values among Exp1, Exp2, and Exp3 range from 0.90 to 0.92 and between Exp1, 2, 3 and Exp4, from 0.72 to 0.76. Analysis of agreement concerning individual biome groups is indicated by individual κ_i ($i = 1, 2, 3, 4$). These values reveal that the difference between Exp1, 2, 3 on the one hand and Exp4 on the other hand can be attributed to sand desert for which $\kappa_4 < 0.35$ in all cases.

To check whether the above-mentioned differences are significant, ensembles of biome patterns are constructed from each experiment using only the iterations of the trend-free part of the iteration series. The ensembles are compared with respect to the area covered by each biome

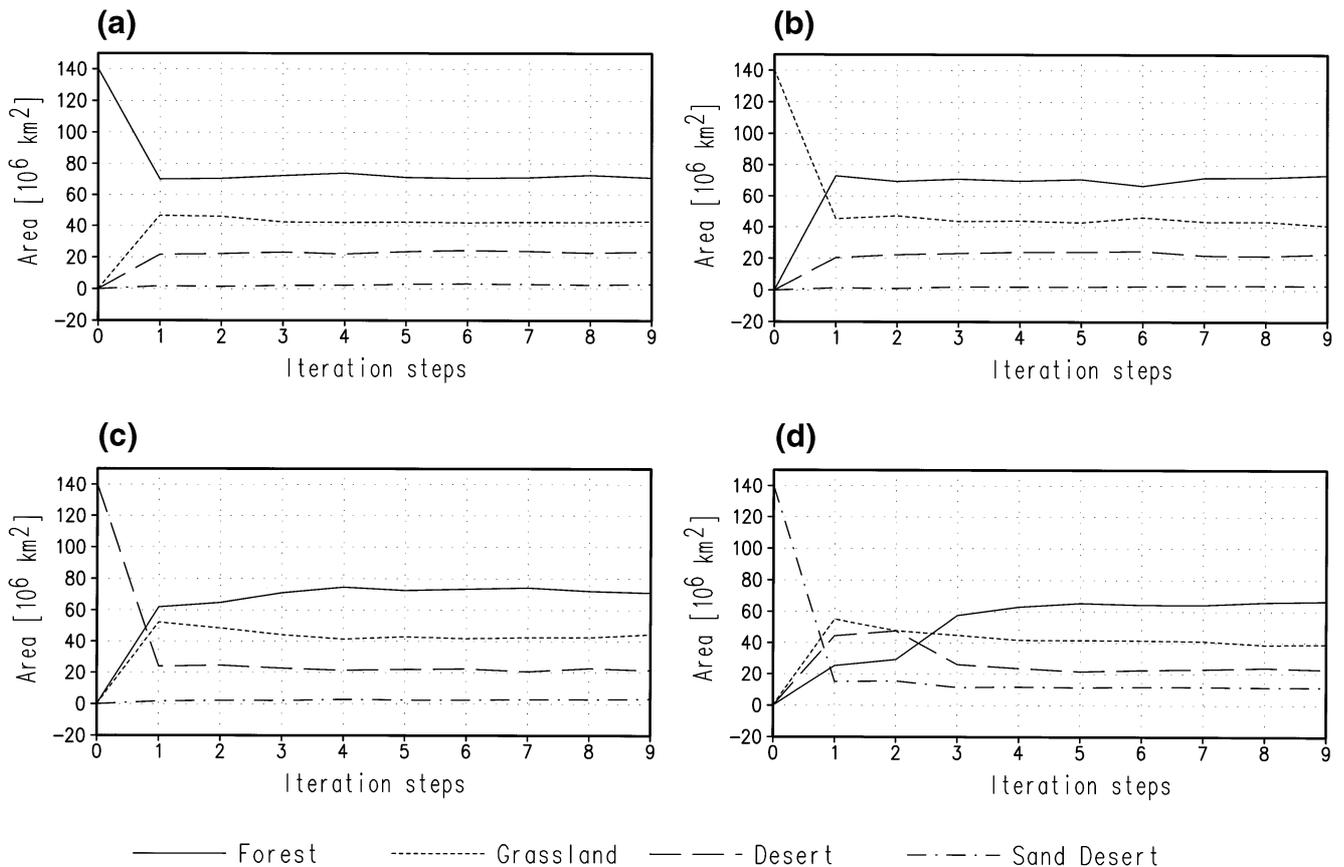


Fig. 2 Areal coverage (in 10^6 km 2) of biome groups as a function of the iteration steps for (a) Exp1; (b) Exp2; (c) Exp3, and (d) Exp4. Full lines refer to forest, dotted lines to grassland, dashed lines to desert, and dash-dotted lines to sand desert. Exp1 is initialized with continents covered only by forest, in Exp2 the initial cover is grassland, in Exp3, desert, and in Exp4, sand desert.

Table 3 Differences between the four experiments in terms of continental area (in 10^6 km 2) covered by biome groups. The numbers indicate differences in forest, grassland, desert, and sand desert, respectively. The value of 0 is assigned if no significant differences are found; otherwise, differences are significant at the 5%-level and, in the case of numbers underlined, at the 1%-level

	Exp1	Exp2	Exp3	Exp4
Exp1	-	0,0,0,0	0,0, <u>1.5</u> ,0	<u>6.6</u> , <u>2.1</u> ,0,- <u>8.9</u>
Exp2		-	0,0,0,0	5.7, <u>3.4</u> ,0,- <u>8.8</u>
Exp3			-	<u>7.6</u> , <u>2.5</u> , <u>1.3</u> ,- <u>8.8</u>
Exp4				-

group. The result of this comparison is summarized in Table 3.

Table 3 has to be read in the following way: when comparing Exp1 with Exp2 (first row, second column) the vector 0,0,0,0 indicates that there is no significant difference in the area covered by each biome group. When comparing Exp1 with Exp4 (first row, fourth column) the vector 6.6,2.1,0,-8.9 indicates that there is

6.6×10^6 km 2 more forest area in Exp1 than in Exp2, 2.1×10^6 km 2 more grassland, and 8.9×10^6 km 2 less sand desert. These differences are significant at the 1%-level. Differences in desert between Exp1 and Exp4 are not significant.

Table 3 reveals that Exp1, Exp2, Exp3 on the one hand and Exp4 on the other hand differ because there is significantly more forest and grassland in the former group of experiments than in Exp4, whereas in Exp4 significantly more sand desert is found. Differences between Exp1, Exp2, and Exp3 are statistically insignificant, with the exception that in Exp1 more desert is detected than in Exp3.

Regional perspective of biome patterns

To explore in which regions on Earth differences between Exp1, Exp2, Exp3 and Exp4 occur, the land area is divided into 9 regions (see Fig. 4). In the land area which is not covered by one of these regions (e.g. the northern part of South America), no differences are found even between the individual iterations of Exp1, Exp2, Exp3 and Exp4.

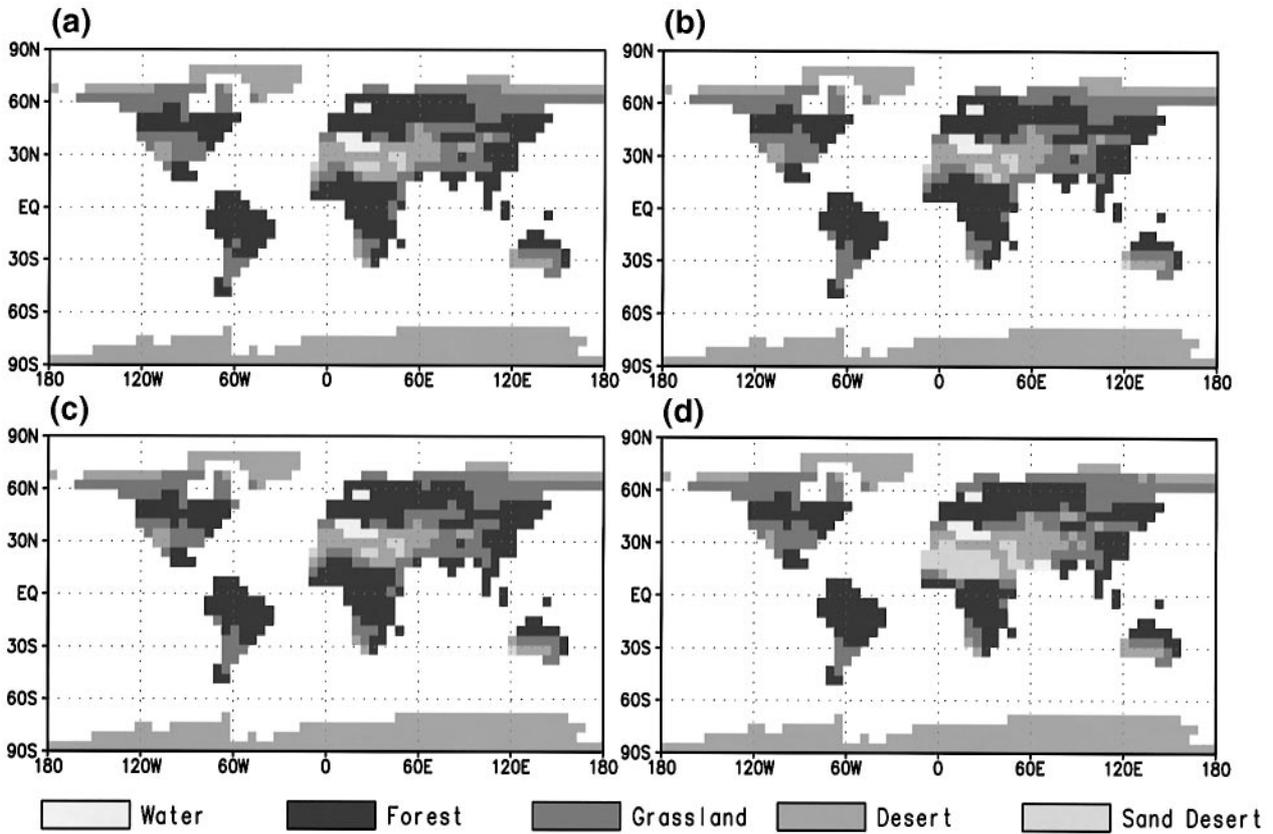


Fig. 3 Biome patterns computed from (a) Exp1; (b) Exp2; (c) Exp3, and (d) Exp4. Black patches indicate forest; dark gray patches, grassland; gray patches, desert; and light gray patches, sand desert.

Table 4 The same as Table 3, except for the region of North Africa (see Fig. 4) only

	Exp1	Exp2	Exp3	Exp4
Exp1	-	0,0,0,0	0,0,0,0	<u>4.8,2.5,1.2,-8.5</u>
Exp2		-	0,0,0,0	<u>4.5,3.2,0,-8.6</u>
Exp3			-	<u>5.5,2.8,0.4,-8.6</u>
Exp4				-

Table 5 The same as Table 3, except for the region of Central East Asia (see Fig. 4) only

	Exp1	Exp2	Exp3	Exp4
Exp1	-	0,0,0,0	0,0,0,6,0	<u>2.4,0,-2.7,0</u>
Exp2		-	0,0,0,7,0	<u>2.9,0,-2.6,0</u>
Exp3			-	<u>3.2,0,-3.2,0</u>
Exp4				-

Significant differences in areal coverage of biome groups occur in the regions of Europe, North Africa, Siberia, and Central East Asia. In the other regions, there

are no significant differences, or if significant, then the differences are very small, i.e. they cover only one or two grid boxes. In North Africa, the largest difference in biome coverage, larger than in any other region, is found: Exp1, Exp2, Exp3 yield more forest, grassland, and desert, but less sand desert. This difference is clearly shown in Fig. 3(a-d) and Table 4. Central East Asia is the region in which the second largest difference occurs; here there is more forest in Exp1, Exp2, Exp3 than in Exp4, but less desert (see Table 5).

Obviously, North Africa and Central East Asia are the regions in which the biogeophysical feedback leads to multiple equilibrium solutions of the atmosphere-biome system. This feedback operates such that in these regions biome groups which occur under conditions of severe drought (i.e. desert and sand desert) are more widespread in Exp4 than in Exp1, Exp2, Exp3. Differences between Exp1, Exp2, Exp3 and Exp4 are also found in Europe where Exp1, Exp2, Exp3 exhibit more forest than Exp4. Comparison of all biome maps (not shown here) reveals that this difference in forest coverage affects the three grid boxes in Scandinavia. Although statistically significant, it

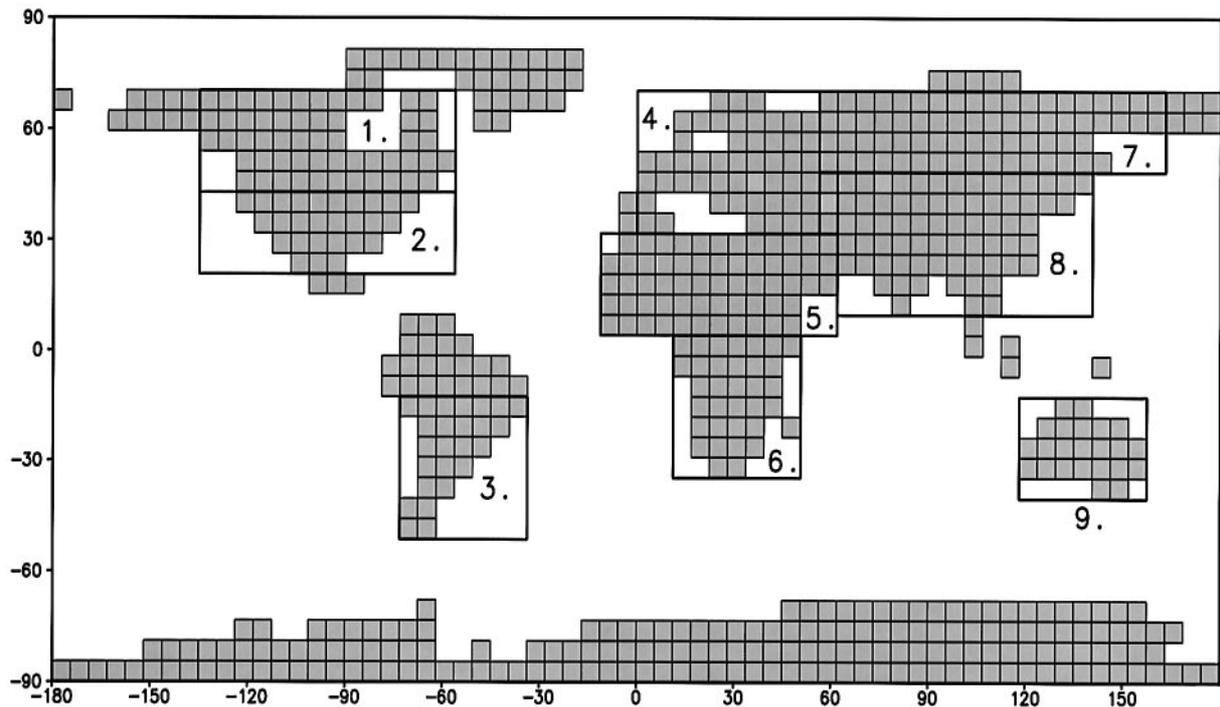


Fig. 4 Geographical locations of areas used for regional investigations. 1: Boreal North America, 2: North America, 3: South America, 4: Europe, 5: North Africa, 6: South Africa, 7: Siberia, 8: Central East Asia, 9: Australia. The fine mesh indicates the spatial resolution of the atmosphere-biome model used in this study.

has to be questioned whether a physical interpretation of this difference is meaningful (see last section).

Differences between Exp1, Exp2, Exp3 are found in Central East Asia and Siberia. In Central East Asia, more desert appears in Exp1 and Exp2 than in Exp3. In Siberia, forest is more widespread in Exp1 than in Exp3.

Atmospheric states

The differences in the atmospheric circulation which lead to differences in biome patterns are best characterized by the so-called velocity potential. The velocity potential has the following meaning. The wind field can be divided into a nondivergent and an irrotational component. Gradients of the velocity potential are proportional to the irrotational, divergent wind. Therefore, the velocity potential is a measure of divergence and convergence of the large-scale atmospheric circulation. Figure 5(a-d) show the velocity potential near the tropopause at 200 hPa (i.e. approximately at heights of 10 km). Negative values of the velocity potential over the Philippines and the Chinese Sea indicate a strong divergence of the circulation there. This is caused by convection, i.e. rising air within the troposphere, the lowest 10 km, above the warm waters of the West Pacific. The centre of convergence near the tropopause, i.e. the region in which the

air descends at a large scale, is located over South Africa in present-day climate.

This dipole of divergence and convergence is found in Exp4 (see Fig. 5d). Obviously, the large-scale atmospheric circulation in Exp4 is close to that typical for present-day climate. Indeed, Exp4 yields almost the same biome patterns (Fig. 3d) as diagnosed from a simulation of present-day climate (Fig. 1b). In the (anomalous) case of a smaller Sahara desert (Exp1, Exp2, Exp3) the centre of convergence shifts westward to the tropical Atlantic (Fig. 5a-c). It can be shown (e.g. Claussen 1997; Kubatzki & Claussen 1997) that this shift is caused by an increase of convection above the more vegetated Sahara.

Why does convection increase above the more vegetated Sahara or, in other words, why is there is stronger sinking motion above the Sahara desert than above the 'green' Sahara? The main aspect of a biogeophysical feedback can be related to processes of desertification in the Sahel as already outlined by Charney. Charney (Charney *et al.* 1975) suggested that a desert is stable because sandy, nonvegetated soil has a much higher albedo than soil covered by vegetation. Therefore, a desert reflects more solar radiation to space than any vegetated area under the same meteorological conditions. Moreover, desert surfaces are hotter than vegetated surfaces, and the air above them is less cloudy. Hence a

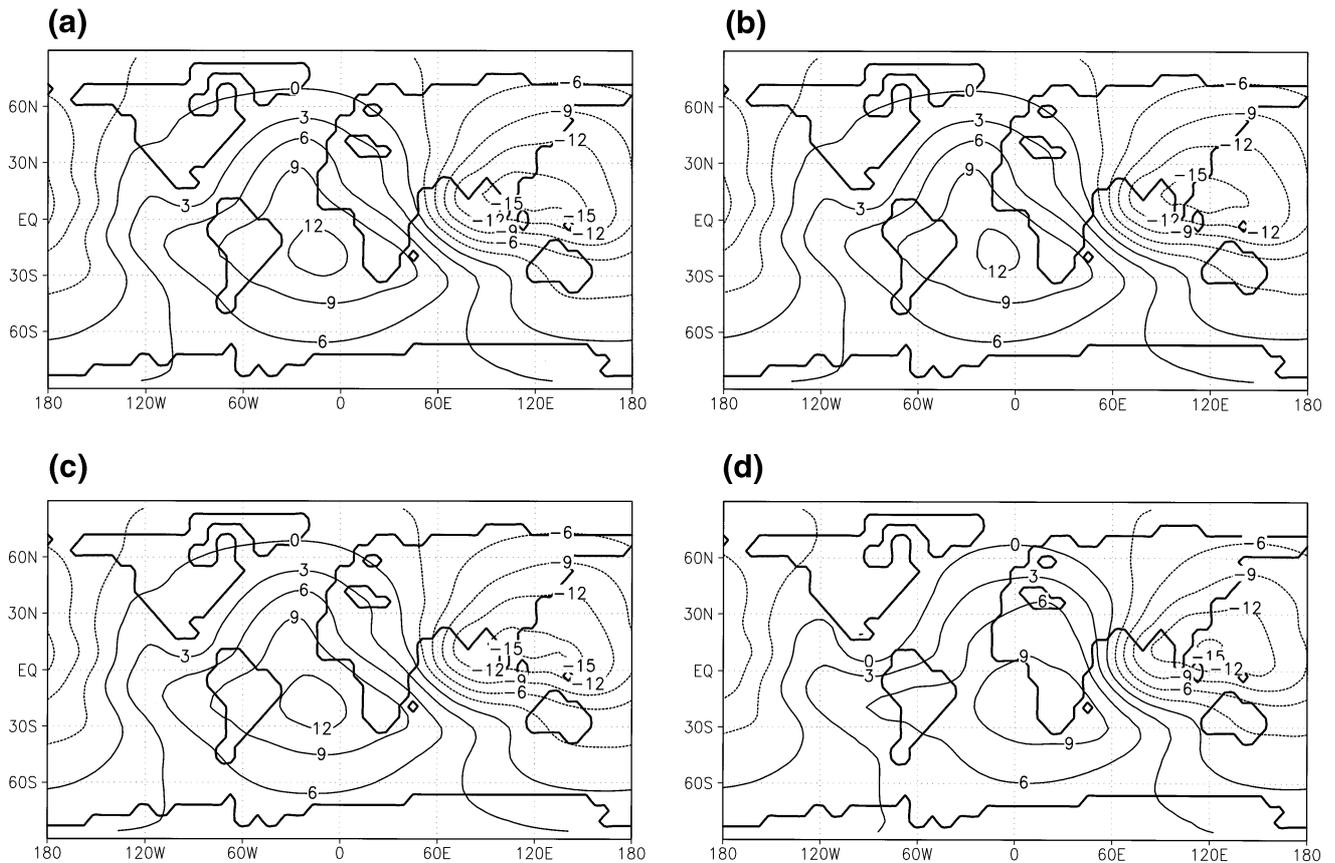


Fig. 5 Global distribution of velocity potential (in km^2/s) near the top of the tropopause at 200 hPa (i.e. at heights of some 10 km) for (a) Exp1; (b) Exp2; (c) Exp3, and (d) Exp4.

desert emits more longwave radiation to space. The net result is that a desert is a radiative sink of heat relative to its surroundings. Because the troposphere above the Sahara is cooler than above the adjacent regions, there is a relative air flow towards the Sahara. The air over the Sahara must descend and compress adiabatically. As a result it becomes warmer and drier. Consequently, the likelihood of precipitation becomes vanishingly small. Moreover, the divergence of near-surface winds becomes stronger over a desert than over a vegetated region. For the Sahel region this implies that the African summer monsoon appears to be weaker in the case of a more widespread desert than in the case of a vegetated Sahel. Since Charney's hypothesis includes only the role of atmospheric moisture convergence, but not surface moisture fluxes, it seems to be applicable not to all subtropical deserts (e.g. Dickinson 1992), but only to processes in the Sahel. Over the Indian subcontinent, a positive feedback between increased soil moisture and stronger summer monsoon can be found – a mechanism proposed by Meehl (1994).

Processes in North Africa and over the Indian subcon-

tinent are coupled by the tropical easterly jet (e.g. Subbaramayya & Ramanadnam 1981) which is found near the tropical tropopause during boreal summer. The tropical easterly jet reaches from the West Pacific to Africa. It has a main branch crossing the equator and a secondary branch north of the equator and it is basically caused by the divergence above the West Pacific and the convergence above South Africa, in the case of Exp1, or the tropical Atlantic, in the case of Exp1, Exp2, Exp3. Obviously, the tropical easterly jet, particularly its branch north of the equator, reaches farther out into the Atlantic in the latter case; moreover, it gets stronger. It can become stronger because the centre of convection over the more vegetated North Africa – and thereby the so-called Hadley cell – moves northward. The upper, equator-bound branch of the Hadley cell feeds the tropical easterly jet by means of the Coriolis force.

These differences in atmospheric circulation caused by the biogeophysical feedback in the Sahara/Sahel region are quite similar to those found in the more regional study by Claussen (1997). Therefore, the reader is referred to the latter study for a more extensive

discussion including a comparison of surface energy budgets.

Discussion and conclusions

The atmosphere–biome system seems to be an intransitive one: depending on the initial conditions, the ECHAM-BIOME model yields two solutions. If the continents are initially covered with sand desert, then the present-day distribution of subtropical desert appears. However, if the continents are initially covered with dark soil or any type of vegetation (either forest or grassland), then the Sahara and Arabian deserts become smaller; moreover, the climate in Central East Asia is less arid. This result is very close to that of a more regional study in which land-surface conditions were changed only in tropical and some subtropical regions (Claussen 1997) – which is a surprising and novel aspect of this study. Therefore, one can conclude that North Africa is the region which is most sensitive to changes in vegetation cover concerning bifurcations of the atmosphere–biome system in present-day climate, i.e. under present-day solar irradiation and present-day ocean circulation.

Can one be sure that North Africa and, to a lesser extent, Central East Asia are the only regions in which multiple equilibrium solutions of the atmosphere–biome system occur? What about the boreal regions, for which a feedback between atmosphere and snow-covered forests has been hypothesized (e.g. Foley *et al.* 1994; deNoblet *et al.* 1996)?

In this study, several significant changes were detected for Europe, more precisely for Scandinavia and for Siberia. However, these changes are hard to interpret. For example, in Siberia, Exp1 which was initialized with forest finally yields more forest than Exp2 which was started with grassland. This difference could be interpreted as a result of a positive feedback: snow-covered grassland receives less solar radiation in spring and early summer which would inhibit the growth of forests because the annual temperature sum becomes too small. If, on the other hand, forest already exists, then the (darker) forested region receives more solar radiation which would favour the persistence of forest. This argument, however, is counteracted by the fact that in Exp3 and Exp4, which are started with bare soil, more forest emerges than in Exp2. Similar arguments apply to the differences seen in Scandinavia.

Apart from physical reasoning, these differences, although statistically significant, should be taken with care from the numerical point of view. As mentioned by v. Storch (1995), atmospheric processes smaller than, say, 4×4 grid boxes cannot be properly represented. Hence evidence that the feedback between atmosphere and

snow-covered boreal vegetation leads to multiple solutions in high latitudes is not found in this study.

Is there any indication that a higher spatial resolution or improved parameterization of near-surface energy transport would affect the above results? Sensitivity studies with the ECHAM-3-BIOME model for different climate conditions of 6000 years ago (Claussen & Gayler 1997) and 21,000 years ago (Kubatzki 1996; Kubatzki & Claussen 1997) reveal a similar picture. If there is any bifurcation of the atmosphere–biome system it appears mainly in North Africa, but not at high latitudes. These simulations are done at T42-resolution, i.e. some $2.8^\circ \times 2.8^\circ$ longitude/latitude, which is twice as fine as the spatial resolution chosen in this study. Also, bifurcation experiments with an updated version of ECHAM, ECHAM-4 (Stahmann 1996), do not exhibit new equilibrium solutions. ECHAM-4 has better physical parameterizations with respect to land-surface processes and radiation transfer (Roeckner *et al.* 1996; Wild *et al.* 1996) which lead to a considerable reduction of the cold bias at high latitudes and of precipitation deficiencies in North America and Australia. Therefore, it is believed that the results of this study are fairly robust.

What has to be done next? First, it is proposed that more sensitivity experiments should be undertaken to strengthen, or to falsify, the hypothesis of multiple equilibrium solutions of the atmosphere–biome system. Completely different models should be used – not just updates and derivatives of ECHAM and BIOME. Improved models of energy transfer between soil, vegetation, and atmosphere would allow us to use more differentiated models of biome dynamics which could yield a more differentiated, but – as outlined above – not necessarily completely different, picture of the stability of the atmosphere–biome system. At the same time so-called 'low order models' (Lorenz 1960) could be constructed which capture the essence of atmospheric and vegetation dynamics using differential equations with a minimum degree of freedom.

Secondly, simulations of palaeoclimates should be extended to explore the possibility of multiple solutions under different boundary conditions. If the conditions are known under which multiple equilibrium solutions appear – and under which conditions there is only one solution – then the mechanism of atmosphere–biome instability can be understood in more detail.

Thirdly, it should be interesting to see whether inclusion of ocean dynamics (including sea ice) could alter the stability of the atmosphere–biome system. Bonan *et al.* (1992) mention that sea ice dynamics tends to enhance the effect of boreal forest on global climate. Moreover, it is known that the atmosphere–ocean system has its own bifurcation dynamics and multiple solutions (e.g. Rahmstorf 1996). Hence an atmosphere–vegetation–ocean

model needs to be set up to explore the role of biogeophysical feedbacks in the climate system fully.

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References

- Arpe K, Bengtsson L, Dümenil L, Roeckner E (1994) The hydrological cycle in the ECHAM3 simulations of the atmospheric circulation. In: *Global Precipitation and Climate Change* (eds Debois M, Deslmand F). NATO ASI Series Vol. I, **26**, 361–377.
- Bengtsson L (1994) Wie gut können wir das Klima mit einem numerischen Modell der allgemeinen Zirkulation simulieren? *Annals of Meteorology*, **29**, 93–132.
- Blondin C (1989) *Research on land surface parameterization schemes at ECMWF*. Proceedings of the workshop on 'Parameterization of fluxes over land surfaces'. ECMWF, Reading UK.
- Bonan GB, Pollard D, Thompson SL (1992) Effects of boreal forest vegetation on global climate. *Nature*, **359**, 716–718.
- Charney JG (1975) Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society*, **101**, 193–202.
- Charney JG, Stone PH, Quirk WJ (1975) Drought in the Sahara: A biogeophysical feedback mechanism. *Science*, **187**, 434–435.
- Claussen M (1994) On coupling global biome models with climate models. *Climate Research*, **4**, 203–221.
- Claussen M (1997) Modeling biogeophysical feedback in the African and Indian Monsoon region. *Climate Dynamics*, **13**, 247–257.
- Claussen M, Gayler V (1997) The greening of Sahara during the mid-Holocene: results of an interactive atmosphere-biome model. *Global Ecology and Biogeography Letters*, in press.
- Dickinson RE (1992) Changes in land use. In: *Climate System Modeling* (ed. Trenberth KE), pp. 698–700. Cambridge University Press, Cambridge.
- Dümenil L, Todini E (1992) A rainfall-runoff scheme for use in the Hamburg GCM. In: *Advances in Theoretical Hydrology* (ed. O'Kane JP). European Geophysical Society Series on Hydrological Sciences, **1**, pp.129–157. Elsevier, Amsterdam.
- Foley J, Kutzbach JE, Coe MT, Levis S (1994) Feedbacks between climate and boreal forests during the Holocene epoch. *Nature*, **371**, 52–54.
- Henderson-Sellers A (1993) Continental vegetation as a dynamic component of global climate model: a preliminary assessment. *Climatic Change*, **23**, 337–378.
- Köppen W (1936) Das geographische System der Klimate. In: *Handbuch der Klimatologie* (eds Köppen W, Geiger, R) Band 5, Teil C. Gebrüder Bornträger, Berlin.
- Kubatzki C (1996) *Numerische Experimentalerimente zu den globalen biogeophysikalischen Wechselwirkungen während des Letzten Glazialen Maximums (21000 Jahre vor heute)*. Diploma thesis, University of Hamburg, 96pp.
- Kubatzki C, Claussen M (1997) Simulation of the global biogeophysical interactions during the Last Glacial Maximum. *Climate Dynamics*, submitted.
- Kutzbach JE, Bonan G, Foley J, Harrison SP (1996) Vegetation and soil feedbacks on the response of the African monsoon to orbital forcing in the early to middle Holocene. *Nature*, **384**, 623–626.
- Leemans R, Cramer W (1991) *The IIASA Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness on a Global Terrestrial Grid*. IIASA Research Report RR-91-18, Laxenburg, Austria.
- Legates DR, Willmott CJ (1990) Mean seasonal and spatial variability in gauge corrected global precipitation. *Journal of Climatology*, **10**, 111–127.
- Lorenz E (1960) Maximum simplification of the dynamic equations. *Tellus*, **12**, 243–254.
- Louis JF (1979) A parametric model of vertical eddy fluxes in the atmosphere. *Boundary-Layer Meteorology*, **17**, 187–202.
- Meehl GA (1994) Influence of the land surface in the Asian summer monsoon: external conditions versus internal feedbacks. *Journal of Climate*, **7**, 1033–1049.
- Monserud RA, Leemans R (1992) Comparing global vegetation maps with Kappa statistic. *Ecological Modelling*, **62**, 275–293.
- deNoblet N, Prentice IC, Jousaume S, Texier D, Botta A, Haxeltine A (1996) Possible role of atmosphere-biosphere interactions in triggering the last glaciation. *Geophysical Research Letters*, **23** (22), 3191–3194.
- Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AM (1992) A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography*, **19**, 117–134.
- Rahmstorf S (1996) On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Climate Dynamics*, **12**, 799–811.
- Ramanathan V, Cess RD, Harrison EF, Minis P, Barkstrom BR, Ahmad E, Hartmann D (1989) Cloud-radiative forcing and climate: results from the Earth Radiation Budget Experiment. *Science*, **243**, 57–63.
- Roeckner E, Arpe K, Bengtsson L, Brinkop S, Dümenil L, Kirk E, Lunkeit F, Esch M, Ponater M, Rockel B, Sausen R, Schlese U, Schubert S, Windelband M (1992) *Simulation of the Present-Day Climate with the ECHAM Model: Impact of Model Physics and Resolution*. Report 93, Max-Planck-Institut für Meteorologie, Hamburg, 171pp.
- Roeckner E, Arpe K, Bengtsson L, Christoph M, Claussen M, Dümenil L, Esch M, Giorgetta M, Schlese U, Schulzweida U (1996) *The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present-Day Climate*. Report 218, Max-Planck-Institut für Meteorologie, Hamburg, 90pp.
- Stahmann M (1996) *Der Einfluß unterschiedlicher Bodentypen auf die von einem globalen Atmosphäre-Biosphäre-Modell berechnete Vegetationsverteilung*. Diploma thesis, University of Hamburg, 81pp.

v.Storch H (1995) Inconsistencies at the interface of climate impact studies and global climate research. *Meteorologische Zeitschrift*, **4** (NF), 72–80.

Subbaramayya I, Ramanadnam R (1981) On the onset of the Indian southwest monsoon and the monsoon general

circulation. In: *Monsoon Dynamics* (eds Lighthill J, Pearce R), Cambridge University Press, Cambridge.

Wild M, Dümenil L, Schulz J-P (1996) High resolution GCM simulations over Europe: surface processes. *Climate Dynamics*, **12**, 755–774.