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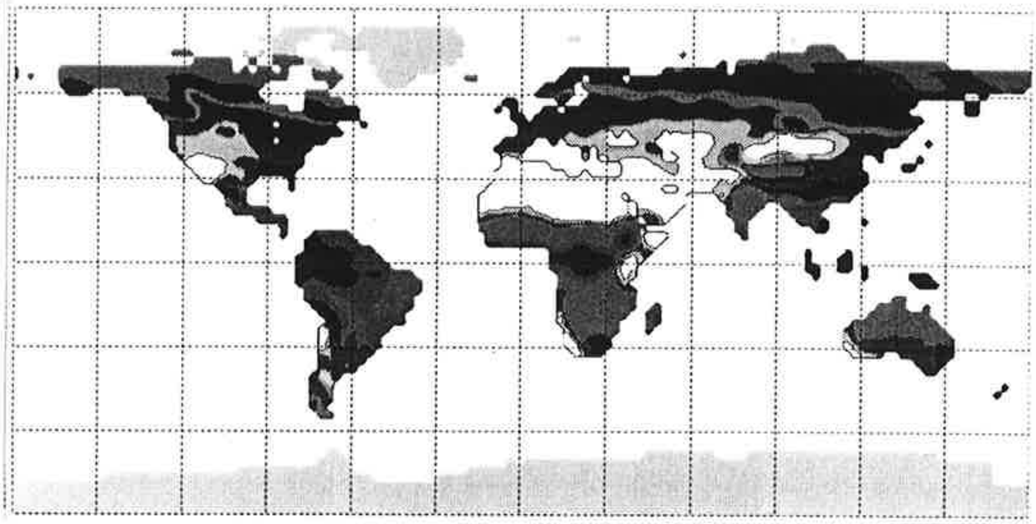

Present biome distributions computed from ECHAM-3-T42 climatology

BIOMES COMPUTED FROM SIMULATED CLIMATOLOGIES

by

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Biomes computed from simulated climatologies*

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Abstract

The biome model of Prentice *et al.* (Journal of Biogeography, 1992a) is used to predict global patterns of potential natural plant formations, or biomes, from climatologies simulated by ECHAM, a model used for climate simulations at the Max-Planck-Institut für Meteorologie. This study is undertaken in order to show the advantage of this biome model in comprehensively diagnosing the performance of a climate model and assessing effects of past and future climate changes predicted by a climate model.

Good overall agreement is found between global patterns of biomes computed from observed and simulated data of present climate. But there are also major discrepancies indicated by a difference in biomes in Australia, in the Kalahari Desert, and in the Middle West of North America. These discrepancies can be traced back to failures in simulated rain fall as well as summer or winter temperatures.

Global patterns of biomes computed from an ice age simulation reveal that North America. Europe, and Siberia should have been covered largely by tundra and taiga, whereas only small differences are seen for the tropical rain forests.

A potential North-East shift of biomes is expected from a simulation with enhanced CO_2 concentration according to the IPCC Scenario A. Little change is seen in the tropical rain forest and the Sahara. Since the biome model used is not capable of predicting changes in vegetation patterns due to a rapid climate change, the latter simulation has to be taken as a prediction of changes in conditions favorable for the existence of certain biomes, not as a prediction of a future distribution of biomes.

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1. Introduction

The correlation between geographic patterns of vegetation and climate has formed the basis for several classification schemes of climate. Probably one of the best-known schemes is that of Köppen (1936). The boundaries used in Köppen's classification of climates are chosen to coincide approximately with vegetational boundaries which are expressed in terms of aspects of climate, included seasonality, that are relevant to plants. Köppen's classification provides a comprehensive view on global distribution of climates. It is, therefore, easily applicable to visualize the effects of climate change on a global scale (e.g. Lohmann *et al.* , 1992).

Here, we propose to use a model of potential natural plant formations, or biomes, directly, instead of a classification scheme like Köppen's - which could be considered as indirectly related to global distribution of natural vegetation. We suggest that a global model of biomes can be used as a tool for, at least qualitatively, diagnosing the performance of a climate model. Moreover, such a model is even better applicable to the assessment of impacts of climate changes on potential natural vegetation patterns and characteristics of the biosphere, such as terrestrial carbon storage, than classification schemes like Köppen's.

We have chosen the global biome model formulated by Prentice *et al.* (1992a). This model is based on physiological considerations rather than on correlations between climatic distribution and biomes as they exist today; therefore, it can be applied to the assessment of changes in natural vegetation patterns in response to changes in climate. However, the biome model is a static equilibrium model. It just computes the geographical distribution of biomes, but it cannot predict changes in biomes due to internal vegetation dynamics. The biome model will be summarized briefly in Section 2.

As an input to the biome model, data of climate simulations are taken from the atmospheric general circulation model ECHAM (spectral model of the European Centre for Medium-Range Weather Forecasts with physics being modified by the Max-Planck-Institut in HAMburg) described in detail by Roeckner *et al.* 1992. The performance of ECHAM is evaluated by comparing computed biomes from simulated and observed climatologies - see Section 3. In Section 4, impacts of simulated climate change on biomes during the last ice age will be assessed. Also, a possible change in conditions favorable for biomes due to simulated future climate change will be explored.

2. The biome model

In the biome model of Prentice *et al.* (1992a) 14 plant functional types are assigned climatic tolerances in terms of amplitude and seasonality of climate variables. The cold tolerance of plants is expressed in terms of minimum mean temperature of the coldest month. Some plant types also have chilling requirements expressed in terms of a maximum mean temperature of the coldest month.

The heat requirement of plant types are given in terms of annual accumulated temperatures over $5°C$, for some plant types a threshold of $0°C$ is used. The heat requirement of some shrub types is given by the mean temperature of the warmest month.

The third basic climatic tolerance is associated with moisture requirement. All plant types, except for desert shrub, have minimum tolerable values of moisture indices. Only tropical raingreen also has an maximum tolerable value. The moisture index is defined as ratio of actual evapotranspiration (AET) and potential evapotranspiration (PET). PET basically depends on net-radiation, i.e. solar radiative input, radiative cooling, and cloudiness. AET, in addition, requires prescription of precipitation and soil water capacity. Hence for evaluation of moisture index, monthly means of temperature, precipitation, cloudiness, and information on soil water capacity are needed as input variables. (Actually the biome model uses sunshine in terms of percentages of possible hours of bright sunshine, i.e. an inverse measure of cloudiness.) From sensitivity studies (not shown here) it turns out that replacing the actual global data of soil water capacity by an average of 150 mm changes results only marginally. Therefore the following computations are always done with soil water capacity set to 150 mm.

The biome model predicts which plant functional type can occur in a given enviroment, i.e. in a given set of climatic variables. Then the biome model selects the potentially dominant plant types, and, finally, biomes arise as combinations of dominant types. In Table 1, the allocation of plant functional types to biomes is summarized.

Prentice *et al.* (1992a) have use the IIASA (International Institute for Applied Systems Analysis) climate data base, described by Leemans and Cramer (1990), and soil texture data (to estimate soil water capacity) from the FAO soils map (FAO, 1974). Their predictions of global patterns of biomes are in good agreement with the global distribution of actual ecosystem complexes being evaluated by Olson *et al.* (1983). Where intensive agriculture has obliterated the natural vegetation, comparison of predicted biomes and observed ecosystems is, of course, omitted. Prentice *et al.* (1992a) predictions are given in Figure 1. Allocation of colors to biomes is given in Table 2.

3. Biomes computed from ECHAM climatology

In the following, the performance of the climate model ECHAM (level ECHAM-3) will be investigated by comparing biomes computed from observed climatic data and estimated from ECHAM climatology. A detailed description of ECHAM is given by Roeckner *et al.* (1992). The ECHAM climate data are obtained from a 10-year integration using a climatology of the annual cycle of sea-surface temperatures for the period 1979-1988 (see Roeckner *et al.* , 1992).

3.a ECHAM-3 resolution T42

The ECHAM-3-T42 data are available on a Gaussian grid with a resolution of approximately 300km$\times$300km. These data, consisting of monthly means of temperature at 2 m above ground, precipitation, and cloudiness, are interpolated to a $0.5° \times 0.5°$ grid and fed to the biome model. Results are depicted in Figure 2.

At a first glance, there is a qualitative agreement between the global distribution of biomes computed from observed and from simulated climatology. However, there are some striking discrepancies.

The Australian desert is almost absent in the simulated climatology, instead savanna covers almost all of the Northern half of Australia. Since hot desert shrub and savanna basically differ in their moisture requirement, this failure can be attributed to an excess of simulated precipitation. Indeed, Figure 4a reveals an excess of precipation during Australia's summertime. Similar is valid for South Africa. There, warm mixed forest is found instead of xerophytic woods, and, in turn, the Kalahari Desert is filled by xerophytic woods.

Another difference is seen in North America There, ECHAM yields too much of warm grass/shrub instead of cool grass/shrub. Both biomes, warm grass and cool grass, have a high drought tolerance, no cold tolerance or chilling requirement is assigned, but they differ in their heat requirements. Hence it is suggested that this failure can be attributed to temperatures during the growing season being simulated too high. This idea is supported by Figure 3b. Presumably, poor resolution of orography is responsible for a part of this failure. Moreover, it apprears that warm grass spreads to much to the East, where one would expect temperate deciduous forest according to Prentice *et al.* (1992a). Since warm grass has a larger drought tolerance than temperate deciduous forest, a difference between modelled and simulated precipitation is also possible. In fact, Figure 4b exhibits a lack of summer rain.

A similar difference between warm and cool grass/shrub is seen in the Asian Steppes. However, close inspection of Figure 3b reveals little difference between observed and simulated temperatures in the region between approximately 60°E and 90°E and around 45°N. Prentice (personal communication) mentions that his biome model overestimates the extent of the Asian Steppes. Prentice blames this on the IIASA climate data set which is rather sparse in certain areas, notably in Siberia.

In Central Siberia taiga and cold deciduous forest are estimated from simulated climate, whereas Prentice *et al.* (1992a) predict also a large area of cool grass/shrub. By comparing both biomes it appears that cool grass has a larger drought tolerance but at the same time a larger heat requirement than taiga. So this failure could be due an underestimation of temperature or an overestimation of precipitation. It turns out that both, summer and winter temperatures are simulated too low by ECHAM-3 (see Figures 3a,b) whereas the difference between observed and simulated rain fall is relatively small (see Figures 4a,b). Likewise the absence of taiga in Alaska in the simulated climate is presumably also caused by an underestimation of temperatures.

There are other small scale differences between biomes in Figure 1 and 2. Some of them can certainly be attributed to the poor resolution of orography as, for example, over the Andes and the Rocky Mountains. Perhaps the same is valid for the Gobi Desert which is a cool desert, but appears as a hot desert in the simulated climate.

3.b ECHAM-3 resolution T21

Performance of a model generally depends on its resolution. The resolution of the Gaussian grid of T42 is approximately 300km x 300km, that of T21, approximately 600km x 600km. The boundary conditions for simulations with ECHAM-3-T21 and with ECHAM-3-T42, shown in the previous section, are the same. In Figure 5, biomes resulting from ECHAM-3-T21 climatology are depicted. By comparing Figures 2 and 5, an overall agreement of global patterns of biomes can be conceded. However, the poorer resolution leads to a poorer prediction of biomes: The Amazonian rain forest unrealistically extends into Central America. Tundra seems to have advanced too far to the South in Central Siberia. In North America, taiga is found too far to the South, and warm grass is diagnosed where it should not. The Coastal Plains are assigned mainly xerophytic woods and temperate deciduous forest instead of a dominant warm mixed forest. In South-West Europe, warm mixed forest appears, unrealistically. In conclusion, ECHAM-3-T42 yields a better prediction of global distribution of biomes than ECHAM-3-T21. Hence ECHAM-3-T42 seems to be a better candidate for a climate model - in keeping with an analysis of Roeckner *et al.* (1992).

3.c ECHAM-2 resolution T21

In the following Section 4.a results from an ice age simulation will be presented which has been undertaken with ECHAM-2-T21. In order to assess differences between simulated climates of the last glaciation and present, simulations of today's climate by ECHAM-2-T21 have to be compared with results from ECHAM-3-T21. ECHAM-2 and ECHAM-3 differ in some of their parameterization schemes of physical processes. Presumably the most important changes concern the parameterization of convection, the prognosis of sea-ice temperatures in ECHAM-3, and the inclusion of a parameterization of gravity wave drag in ECHAM-3-T42 (in ECHAM-3-T21 the latter is also omitted). For details see Roeckner *et al.* (1992). By comparing Figures 5 and 6 differences between simulated climatologies outputs from ECHAM-3-T21 and ECHAM-2-T21 in terms of global patterns of biomes become evident.

The worst change is seen for the tropical rain forests, particularly in Africa, which are poorly represented by ECHAM-2. In Europe, cool mixed forest spreads too far to the West. Likewise, the excess of cool mixed forest in North Amercia is even worse in ECHAM-2. But it is better in other aspects. In Siberia, distribution of taiga and tundra is more realistic. In South Africa and Australia, xerophytic woods are widely spread, indicating a drier climate as predicted by ECHAM-3-T21 and T42. But still, the Australian Desert is missing.

4. Assessment of climate change

4.a An ice age simulation (18000 years B.P.)

For the ice age experiment presented here Lautenschlager (personal communication) has used the following boundary conditions: Orbital parameters were left unchanged. (The rather small glacial changes in the orbital parameters would have reduced the July insolation at 65°N only by about 1%.) For the albedo and the vegetation parameters over ice-free continents, the modern values are left unchanged, because the CLIMAP (1981) reconstruction is controversial to more recent ones by Frenzel *et al.* (1992). The atmospheric CO_2-concentration was set to 200 ppm. For surface elevation of the glacial ice sheets the minimum reconstruction by Frenzel *et al.* (1992) was used. The SST anomalies were taken from CLIMAP (1981) for February and August and interpolated between February and August by a cosine function. The ECHAM-2-T21 simulation of the last glacial maximum is taken as the average over the last 10 annual cycles of a 15-year simulation. With a very few, minor exception, this simulation agrees with earlier ones obtained by a 6-year integration using ECHAM-1-T21. The latter simulations are described in detail by Lautenschlager (1991) and Lautenschlager and Herterich (1990).

Global patterns of biomes computed from the simulated ice age climatology are depicted in Figure 7. The tropical rain forest in Africa has expanded, in South America, the Amazonian rain forest has become smaller, but there is a larger region of the Brazilian Highlands covered by rain forest. However, in the light of the above mentioned failures of ECHAM-2-T21, this result has to be taken with care. In Africa, the Sahara has moved southward. The Libyan Desert has become a cool desert. In Australia, hot desert has developed. Largest changes compared to present distributions are seen in North America, Europe, and Siberia, of course. Most of Europe is covered by tundra and taiga. followed to the south by cool grass and shrub. This agrees qualitatively with estimates by Frenzel *et al.* (1992), but it is at variance with earlier data by CLIMAP (1981) which indicate forests and thickly vegetated land at the south rim of the European ice sheet. The cool grass / shrub in Southern Europe agrees favorably with the observed occurence of Loess Steppe. Over North America, Frenzel *et al.* (1992) suggest steppe at the rim of the ice sheet followed mostly by subalpine and subboreal open coniferous, containing large steppe areas to the South. CLIMAP (1981) data reveal simply forests for most of North America. Our results are somewhat closer to Frenzel's *et al.* (1992), although the broad band of temperate deciduous forest is missing in Frenzel's *et al.* (1992) data. Biomes in Central Amercia seem to stay unchanged. Generally, in the Northern Hemisphere, the change in biomes when moving from North to South is more drastic; in Europe cool mixed forest and temperate deciduous forest almost disappear in the ice age simulation.

4.b Future climate from Scenario A

Perlwitz (1992) used ECHAM-3-T42 for studying the climatic impact of CO_2 forcing. As boundary conditions, Perlwitz took observed climatological SST data for the period 1979-1988 and superimposed the SST change obtained from the last 10 years of a transient 100-year integration with the coupled ocean/atmosphere general circulation model ECHAM-1-T21/LSG (Cubasch *et al.* 1992). For the latter, the CO_2 increase was prescribed according to the Intergovernmental Panel on Climate Change (IPCC)

Scenario A. (In these 10 years, the average amount of CO_2 was set to 1145 ppm, and the global mean near surface temperature is approximately 2.4 °C higher than today.)

The resulting biomes from ECHAM-3-T42 are shown in Figure 8. Before discussing Figure 8, however, it has to be stated - and has always to be kept in mind - that Figure 8 *does not* represent a future distribution of biomes. It just interprets the effects of climate change in terms of a *change of conditions* favorable for certain biomes. The biome model itself is unable to predict a change of vegetation due to a rapid change of climate. The biome model just diagnoses potential natural vegetation in the state of an equilibrium with climate conditions.

Comparison of Figures 2 and 8 reveals the following. A climate change would alter the conditions for tropical rain forest only marginally. There is also little change in the conditions for the Sahara as well as warm grass and xerophytic woods south of it. On the Indian Subcontinent, conditions favorable for savanna are found to move into today's Indian Desert. In South America conditions favorable for xerophytic woods are found to spread southward. Likewise conditions for savanna move southward in South Africa and Australia - which has to be judged, however, in the light of ECHAM-3's imperfect simulation of the present climate in these regions. In Europe, Siberia, and North Amercia, a North-East shift of climate is observed. Conditions favorable for xerophytic woods are seen in France, those for warm mixed forest appear over the British Islands. Conditions favorable for warm grass appear over South-East Europe, indicating potential expansion of the Asian Steppes into Europe. Conditions favorable for temperate deciduous forest spread into Sweden, conditions for taiga force back those for tundra - also seen in Siberia and Alaska.

I appears that changes in conditions for boreal biomes, as tundra, taiga, and cold deciduous forest, are strongest. This result agrees with Leemans' (1990) study. Leemans uses the Holdrige classification to assess impacts on natural vegetation due to a global warming. However, like the biome model of Prentice *et al.* (1992a), Holdrige's model is an equilibrium model whose results have to be interpreted cautiously - as also stated by Leemans.

5. Conclusion

The biome model of Prentice *et al.* (1992a) has been used to predict global patterns of potential natural plant formations from climatologies simulated by ECHAM. The motivation is twofold: a qualitative test of simulated climatologies and an assessment of the effects of climate change.

By comparing global patterns of biomes computed from observed and simulated climate data, the performance of ECHAM is qualitatively diagnosed. The most important result is that a good overall agreement between simulation and observation has been found. There are also discrepancies which can be traced back to failures in simulated rain fall as well as summer or winter temperatures. However, a diagnosis of climate simulations by evaluating global patterns of potential natural vegetation does not replace a detailed diagnosis of conservative variables and their fluxes, but it provides a first, more qualitative view on the performance of a model, and it readily points at major problems.

Since the simulated climatology of ECHAM yields a reasonable representation of the present global distribution of potential natural vegetation it seems worthwhile to assess changes of potential natural vegetation in response to simulated changes in climate. As an example, global patterns of biomes have been computed from an ice age simulation 18000 years B.P. Because there is a controversial discussion on the vegetation cover of the Northern Hemisphere during the last glacial maximum, the performance of ECHAM cannot be judged. Our estimates seem to be closer to a recent reconstruction by Frenzel *et al.* (1992) than to an earlier one by CLIMAP (1981). Nevertheless, it is suggested that a climate model should provide guidance for reconstructing past global patterns of vegetation. Since it has been recognized that ECHAM-2-T21, the version of ECHAM used for the ice age run, has some deficiencies in simulating present-day's climate, the ice age run will be repeated using ECHAM-3-T42.

Biomes have also been predicted from a simulation with enhanced CO_2 concentration according to the IPCC Scenario A. It appears that the largest changes occur for boreal biomes, whereas little change is seen for the Sahara and the tropical rain forests. However, since the biome model is not capable of predicting changes in vegetation patterns due to a rapid climate change, this simulation has to be taken as a prediction of changes in conditions favorable for the existence of certain biomes, not as a prediction of a future distribution of biomes. Subsequent studies should, therefore, couple a dynamic model of vegetation succession to a climate model. Candidates for a dynamic model are, for instance, gap-models like FORSKA by Prentice *et al.* (1992b) being developed to simulate the response of boreal forests to rapid changes in climate.

For a closer look into regions, a limited area model being nested into a climate model should be used - which will be the next step to be undertaken. Furthermore, the sensitivity of a climate model to changes in global patterns of biomes will be investigated. The latter requires a quasi-interactive coupling of a biome model to a climate model. It is suggested that studies like these should be prerequisite to studies of impacts of climate changes on the biosphere.

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Table 1: Allocation of plant types to biomes in Prentice's *et al.* (1992a) biome model.

Plant types	Biome name
tropical evergreen =	tropical rain forest
tropical evergreen +	
tropical raingreen =	tropical seasonal forest
tropical raingreen =	savanna
warm-temperate evergreen =	warm mixed forest
temperate summergreen +	
cool-temperate conifer +	
boreal summergreen =	temperate deciduous forest
temperate summergreen +	
cool-temperate conifer +	
boreal conifer +	
boreal summergreen =	cool mixed forest
cool-temperate conifer +	
boreal conifer +	
boreal summergreen =	cool conifer forest
boreal conifer +	
boreal summergreen =	taiga
cool-temperate conifer +	
boreal summergreen =	cold mixed forest
boreal summergreen =	cold deciduous forest
sclerophyll/succulent =	xerophytic woods / shrub
warm grass / shrub =	warm grass / shrub
cool grass / shrub +	
cold grass / shrub =	cool grass / shrub
cold grass / shrub =	tundra
hot desert shrub =	hot desert
cool desert shrub =	cool desert
ice / polar desert =	ice / polar desert

Table 2: Allocation of colors used in Figures 1-2,5-8 to biomes.

- Tropical Rain 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
- Warm Grass/Shrub
- Cool Grass/Shrub
- Tundra
- Hot Desert
- Cool Desert
- Ice/Polar Desert

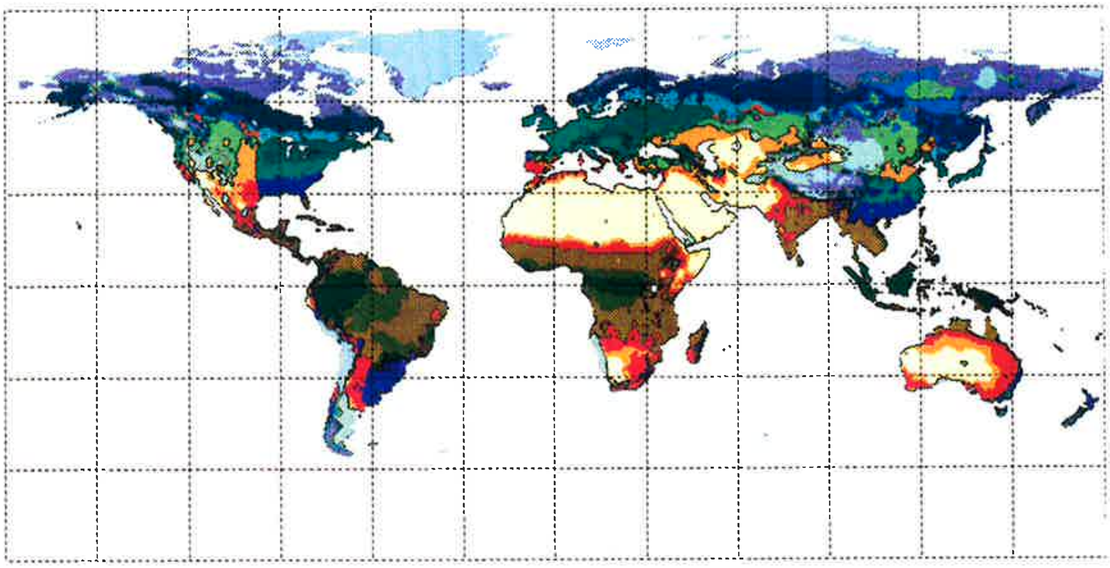

Figure 1: Present biome distributions computed from observed climatology (IIASA data).

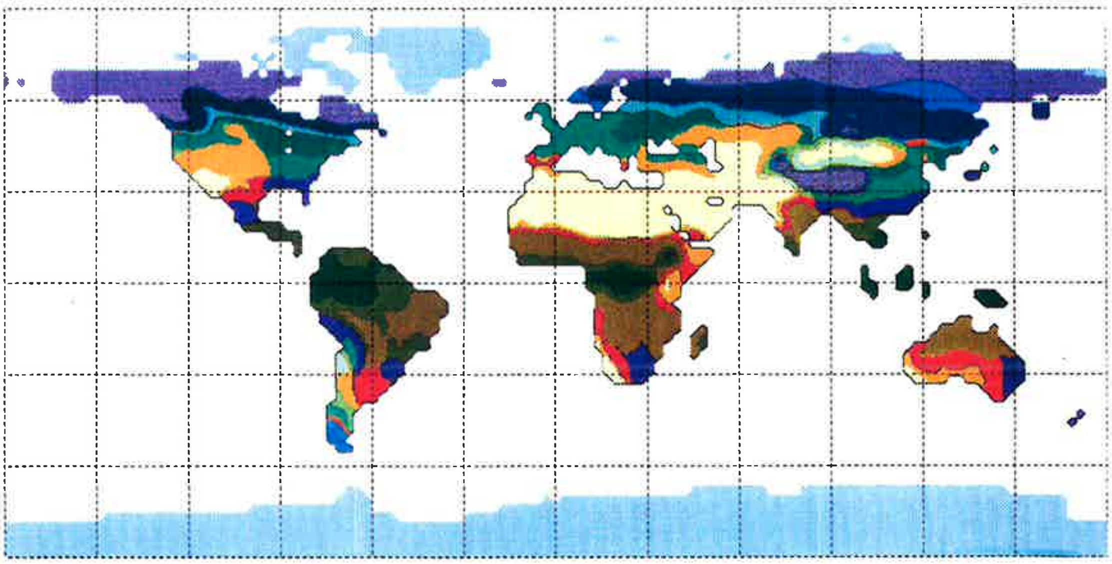

Figure 2: Present biome distributions computed from ECHAM-3-T42 climatology.

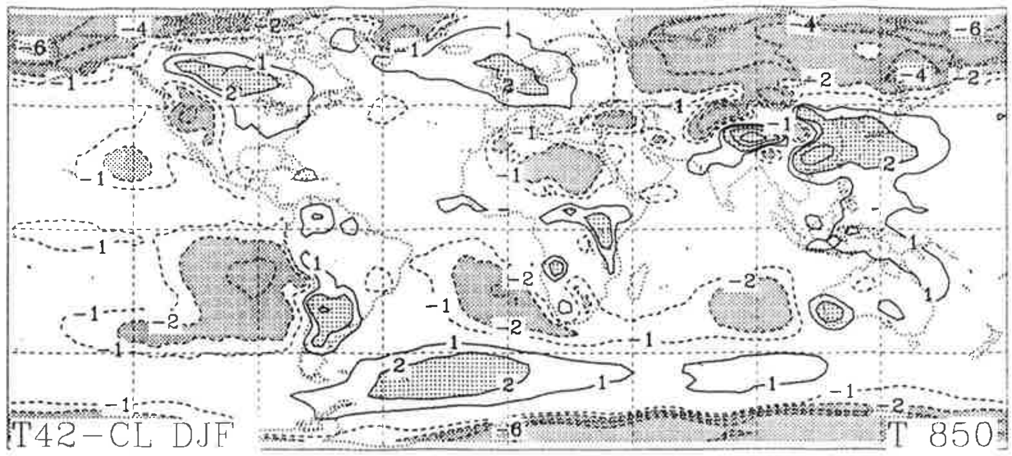

Figure 3a: Difference between observed and simulated (by ECHAM-3-T42) temperatures at 850 hPa in winter (DJF: December, January, February), Figure 3a is taken from Roechner *et al.* (1992).

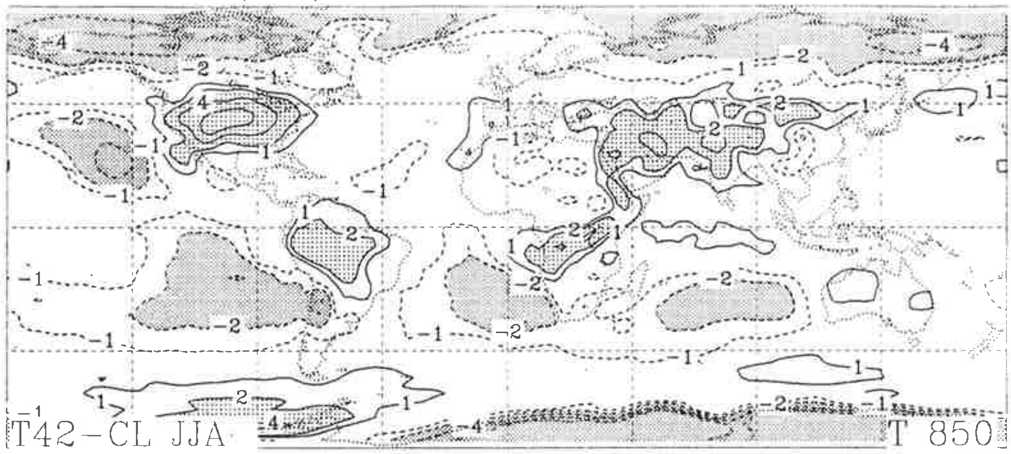

Figure 3b: Same as Figure 3a, but for summer (JJA: June, July, August).

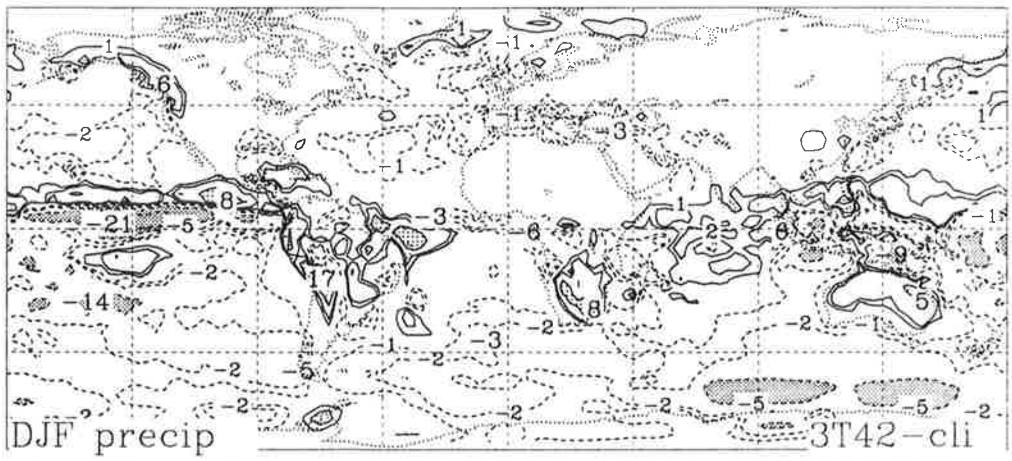

Figure 4a: Difference between observed and simulated (by ECHAM-3-T42) precipitation in winter (DJF: December, January, February). Figure 4a is taken from Roechner *et al.* (1992).

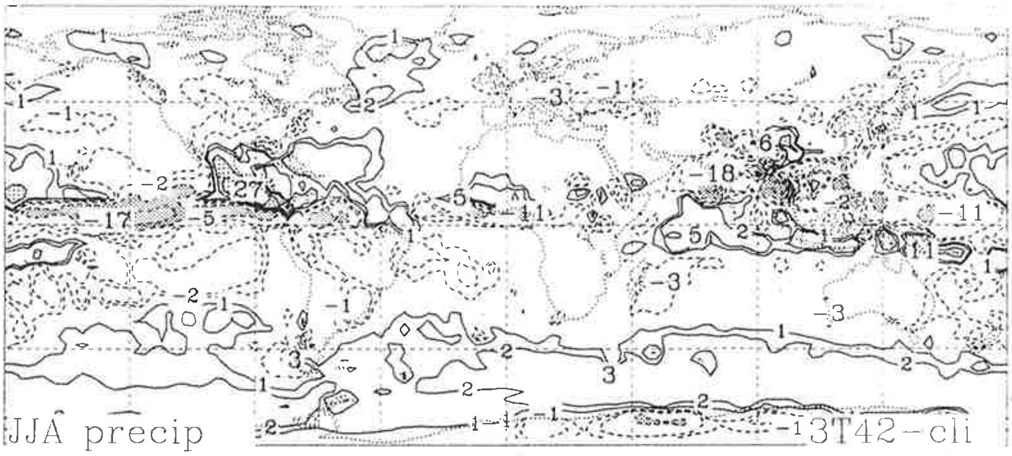

Figure 4b: Same as Figure 4a, but for summer (JJA: June, July, August).

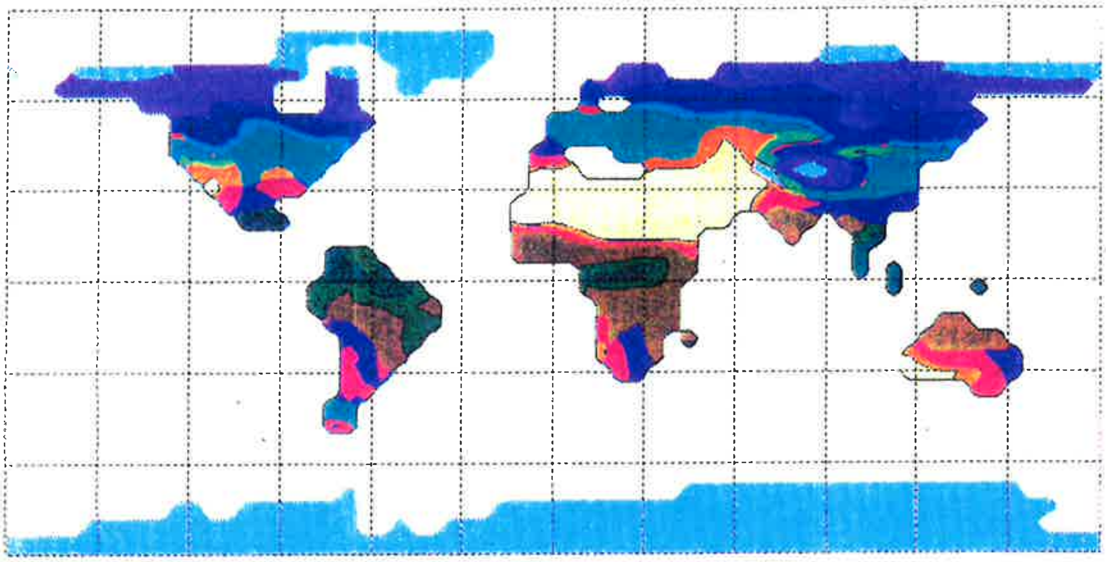

Figure 5: Present biome distributions computed from ECHAM-3-T21 climatology.

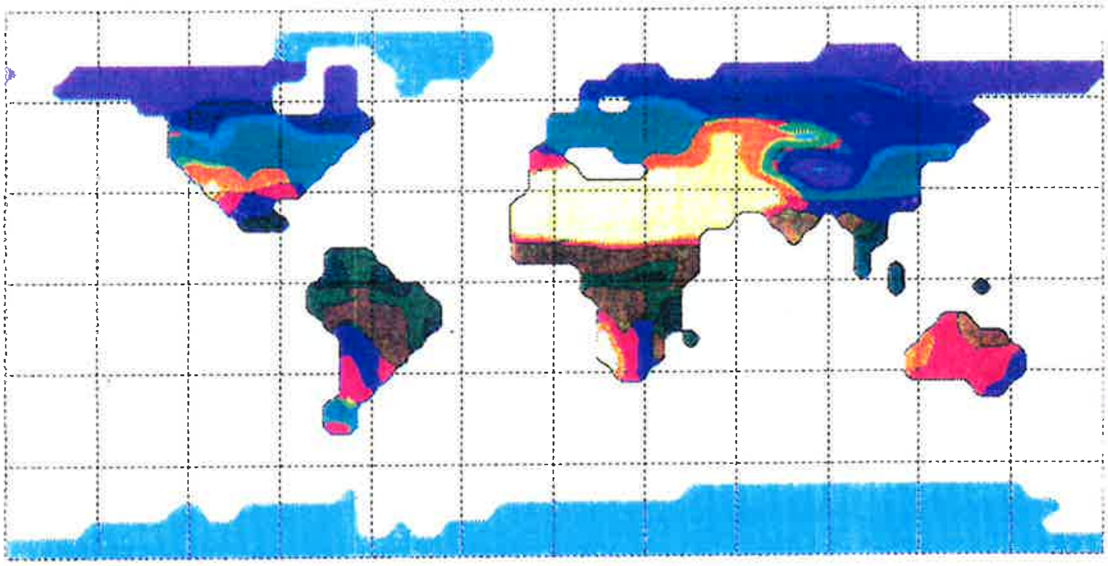

Figure 6: Present biome distributions computed from ECHAM-2-T21 climatology.

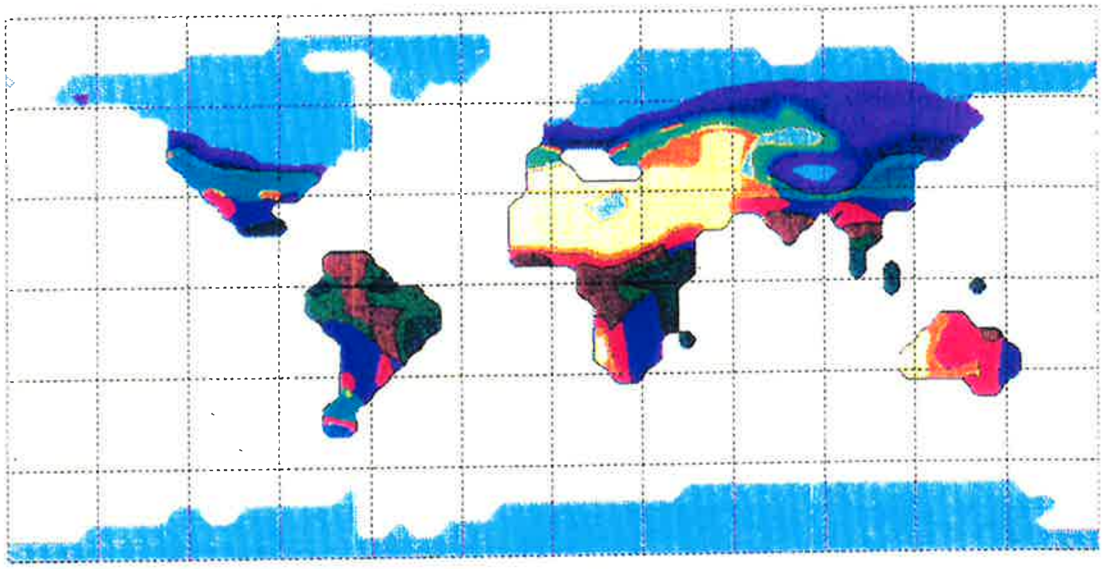

Figure 7: Biome distributions computed from ECHAM-2-T21 simulation of the last glacial maximum (18000 years B.P.)

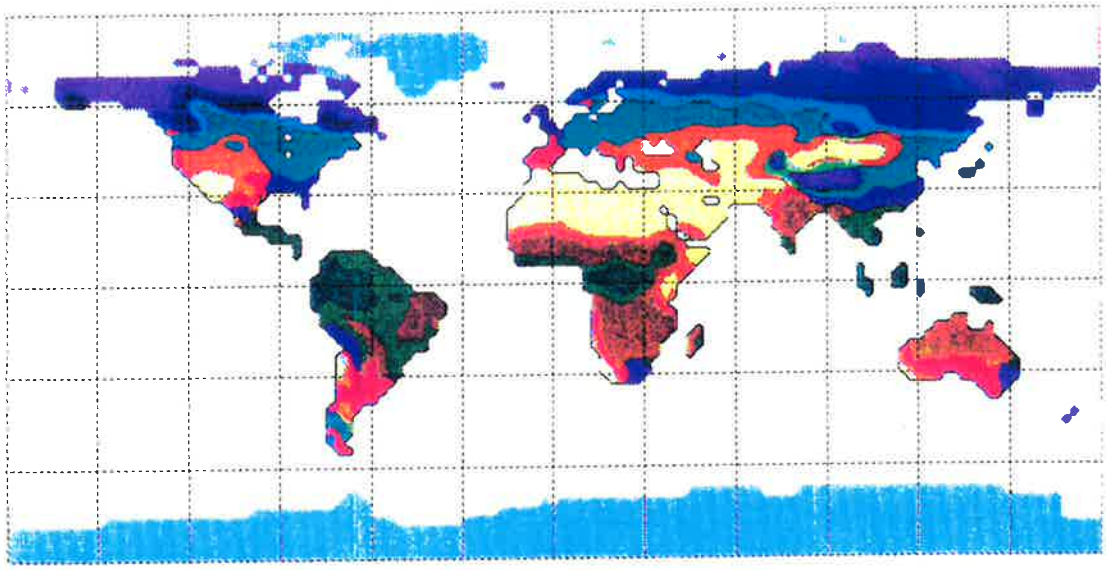

Figure 8: Change of conditions favorable for biomes due to a climate change associated with an increase of CO_2 computed from an ECHAM-3-T42 simulation.