GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 9, PAGES 897-900, MAY 4, 1992

# THE CLIMATE INDUCED VARIATION OF THE CONTINENTAL BIOSPHERE : A MODEL SIMULATION OF THE LAST GLACIAL MAXIMUM

P. Friedlingstein[1,3], C. Delire[2], J.F. Müller[3] and J.C. Gérard[2]

*Abstract.* A simplified three-dimensional global climate model was used to simulate the surface temperature and precipitation distributions for the Last Glacial Maximum (LGM), 18 000 years ago. These fields were applied to a bioclimatic scheme wich parameterizes the distribution of eight vegetation types as a function of biotemperature and annual precipitation. The model predicts a decrease, for LGM compared to present, in forested area balanced by an increase in desert and tundra extent, in agreement with a reconstruction of the distribution of vegetation based on paleodata. However, the estimated biospheric carbon content (phytomass and soil carbon) at LGM is less reduced than in the reconstructed one. Possible reasons for this discrepancy are discussed.

## Introduction

Analysis of air bubbles in ice cores has clearly established that the atmospheric concentration of carbon dioxide during the Last Glacial Maximum, 18000 years ago, was about 75 ppm less than the preindustrial (interglacial) level. A larger content of carbon in the terrestrial biosphere during glacial periods could be a possible cause of this low atmospheric $CO_2$ concentration. Transfer of carbon from the biosphere to the atmosphere could thus explain the rise in atmospheric $CO_2$ concentration between LGM and the preindustrial times.

Using a general circulation model and a bioclimatic scheme, Prentice and Fung (1990) estimated that the amount of carbon in the vegetation and soils at LGM was approximately equivalent to the present interglacial. They found that 200 Gt of carbon were stored by vegetation and soils on land exposed by the low sea level 18 kyr ago. This additional carbon pool at LGM has almost exactly counterbalanced the lower amount of carbon stored by vegetation and soils on the present land area. They concluded that carbon transfer between the biosphere and the atmosphere should not have been a dominant factor in the large atmospheric $CO_2$ level change between glacial and interglacial events. In contrast, Adams et al. (1990), basing their estimates on palynological, pedological and sedimentological data, found that the amount of carbon stored in the biosphere may have been smaller by more than 1000 Gt of carbon at LGM than during the Holocene, corresponding to a doubling in the terrestrial carbon content from LGM to present interglacial. This result has important implications on the ability of the ocean to store the large amounts of carbon that may have been transfered to the atmosphere-biosphere system since the LGM. The contrast between the two sets of results was already present in the reconstruction they made of the vegetation distribution at the LGM. According to Adams et al. (1990), drier vegetation types having a low carbon storage per unit area, such as desert and arid scrub, were much more extensive 18 kyr ago than they are currently. Moist climate types (with high carbon storage) were almost absent from the large areas which they occupy today. In contrast, following the simulation made by Prentice and Fung (1990), the driest vegetation types would have covered a smaller area than today.

The aim of this study is to simulate the climate and the distribution of vegetation types at LGM and to compare it to the reconstruction made by Adams et al. Discrepancies between this work and that of Prentice and Fung are also discussed.

[1] Université Libre de Bruxelles, [2] Institut d'Astrophysique - Université de Liège, [3] Institut d'Aéronomie Spatiale - Bruxelles



Paper number 92GL00546
0094-8534/92/92GL-00546$03.00

## The atmospheric model and the bioclimatic scheme

The model used for this work is the quasi-three dimensional global climate model developed by Sellers (1983, 1985). Description of this model and discussion of its ability to reproduce the present climate can be found in the original papers. Most of the major features of the sea level pressure and temperature fields are quite well simulated. As it is the case for most GCMs, the simulated precipitation field presents some discrepancies with the observed field. For present conditions, it yields a global average sea level temperature of 289.6 K and total precipitation of 2.3 mm/day.

An empirical model of the biosphere has been developed. It predicts the global distribution of the vegetation types and the main carbon pools and fluxes from two climatic variables: the annual precipitation and the biotemperature (the biotemperature is the mean annual temperature (in °C) considering only positive monthly temperatures). Starting from the World Ecosystem Database of Olson et al. (1985) which includes 52 ecosystems on a 0.5°× 0.5° resolution grid, we define eight broad vegetation types (numbers in parenthesis refer to Olson's classification): perennial ice (17,69-71), desert and semi-desert (49-51), tundra (53,63), coniferous forest (20-23,57,60-62), deciduous forest (24-26, 46,48,56), grassland and shrubland (40-42,47,52,59,64), seasonal tropical forest (27,28,32,43) and evergreen tropical forest (29,33). Present-day 5°× 5° annual precipitation and biotemperature distributions were derived from monthly mean climatological fields of precipitation (Shea, 1986) and surface temperature (Trenberth et al., 1988). The relationship between the spatial distribution of each vegetation type and the two climatic variables was then determined empirically. Each vegetation type is allowed to exist within a defined domain of precipitation and biotemperature (Table 1). The vegetation distribution predicted by this bioclimatic scheme, for present-day precipitation and temperature fields, agree with Olson's database. The limited resolution of the model generate some discrepancies when compared with the data, particularly in mountainous regions. Net primary productivity (NPP), phytomass and soil organic carbon pool are calculated as follows. The Miami model (Lieth, 1975) is modified by expressing NPP as the minimum value of two functions, the first depending on mean annual precipitation and latitude, the second depending only on biotemperature.

$$\mathrm{NPP} = \min(f_{BT}, f_P)$$

with

$$f_{BT} = 69.1875 \times \mathrm{BT} \qquad \text{if BT} < 8\ ^\circ\mathrm{C}$$
$$\phantom{f_{BT}} = 1350. \times (1. + \exp(\tfrac{1}{1.315 - 0.119 \times BT})) \qquad \text{if BT} > 8\ ^\circ\mathrm{C}$$

$$f_P = 1125. \times (1. - \exp(-6.64 \times 10^{-4} \times \mathrm{P})) \qquad \text{in the tropics}$$
$$\phantom{f_P} = 1350. \times (1. - \exp(-6.64 \times 10^{-4} \times \mathrm{P})) \qquad \text{in other regions}$$

BT = biotemperature expressed in °C
P = annual precipitation expressed in mm/y
NPP = net primary production expressed in $gC/m^2/y$.

The parameters were adjusted to fit the global NPP distribution given by Fung et al. (1983). The global annual NPP predicted by the model is 53 gtC/yr. The living phytomass (Table 2, Column 4) is calculated as the product of NPP and the mean residence time for carbon in herbaceous and woody biomass in the different vegetation types derived from Goudriaan et al. (1984). Values adopted are listed in Table 3. Finally, soil carbon is inferred from Post et al's study (1982) which relates this variable to biotemperature and annual precipitation.

Table 1. Minimum biotemperature ($BT_m$) and maximum biotemperature ($BT_M$) (in °C) for different annual precipitation levels (in mm/yr) allowing the existence of each vegetation type (refer to Table 2, Column 1).

| Vegetation type | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitations | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ | $BT_m$ | $BT_M$ |
| 10 | 0. | 5.0 | 4.0 | - | | | | | | | | | | | | |
| 50 | 0. | 5.0 | 4.0 | - | 0.6 | 4.0 | 2.5 | 4.0 | | | | | | | | |
| 60 | 0. | 0.6 | 4.0 | - | 0.6 | 4.0 | 2.5 | 4.0 | | | | | | | | |
| 80 | 0. | 0.6 | 4.0 | - | 0.6 | 4.0 | 2.5 | 4.0 | | | | | | | | |
| 100 | 0. | 0.8 | 4.0 | - | 0.6 | 4.0 | 2.5 | 4.1 | | | 4.0 | 4.0 | | | | |
| 130 | 0. | 1.0 | 4.0 | - | 0.6 | 4.0 | 2.5 | 4.5 | | | 4.3 | 6.0 | | | | |
| 160 | 0. | 1.0 | 7.0 | - | 0.6 | 4.0 | 2.5 | 4.7 | | | 4.4 | 28.0 | | | | |
| 200 | 0. | 1.0 | 10.0 | - | 0.6 | 4.0 | 2.5 | 5.0 | | | 4.5 | - | | | | |
| 230 | 0. | 1.0 | 15.0 | - | 0.6 | 4.1 | 2.5 | 5.5 | | | 4.7 | - | | | | |
| 300 | 0. | 1.0 | | | 0.6 | 4.2 | 2.5 | 6.5 | | | 5.0 | - | | | | |
| 400 | 0. | 0.8 | | | 0.6 | 4.4 | 2.7 | 7.2 | | | 6.2 | - | | | | |
| 500 | 0. | 0.7 | | | 0.6 | 4.6 | 3.0 | 8.0 | 8.5 | 8.5 | 7.2 | - | | | | |
| 600 | 0. | 0.7 | | | 0.6 | 4.7 | 3.2 | 8.7 | 8.5 | 17.6 | 8.8 | - | | | | |
| 700 | 0. | 0.7 | | | 0.6 | 4.7 | 3.4 | 9.2 | 9.1 | 18.7 | 17.4 | - | | | | |
| 800 | 0. | 0.7 | | | 0.6 | 5.2 | 3.5 | 10.0 | 9.5 | 19.5 | 19.1 | - | 20.8 | 20.8 | | |
| 900 | 0. | 0.7 | | | 0.6 | 5.2 | 3.8 | 11.0 | 9.9 | 20.0 | 20.2 | 26.6 | 20.0 | 35.0 | | |
| 1000 | 0. | 0.7 | | | 0.6 | 5.2 | 4.0 | 11.5 | 10.0 | 20.7 | 21.4 | 25.7 | 20.0 | - | | |
| 1100 | | | | | 0.6 | 5.3 | 4.2 | 11.5 | 10.0 | 20.8 | 23.4 | 23.4 | 20.2 | - | | |
| 1300 | | | | | 0.6 | 5.5 | 4.6 | 11.5 | 10.0 | 21.1 | | | 20.7 | - | | |
| 1500 | | | | | 0.6 | 5.5 | 4.7 | 11.5 | 10.0 | 21.2 | | | 20.8 | - | 23.0 | 23.0 |
| 2000 | | | | | 0.6 | 5.5 | 4.8 | 11.5 | 10.0 | 21.3 | | | 21.0 | - | 23.0 | 35.0 |
| 3000 | | | | | 0.6 | 5.5 | 5.0 | 11.5 | 10.0 | 21.3 | | | 21.1 | 23.0 | 22.7 | - |

## Glacial climate simulation

In order to simulate the climate of the Earth during the Last Glacial Maximum, 18000 years ago, some input parameters and boundary conditions of the model were changed. The orbital parameters were taken from Berger (1978). The atmospheric $CO_2$ concentration was decreased to 200 ppm, in agreement with the $CO_2$ measurements from the Vostok ice core (Barnola et al., 1987). Coastlines were modified assuming a sea level drop of 130 m (Climap, 1976). Sea ice and snow cover were taken from Climap for February and August. Their annual cycle was approximated by a sine function with February and August values taken as extrema. The model was run to steady state for the present day and the LGM conditions. The difference between the simulated temperature field for the present and for the LGM was then added to the observed temperature field above mentioned. The same was done for the precipitation field. In this way, the simulated climate change was rooted in the observed climatology and the effect of the systematic errors of the model was minimized. In this simulation, the global temperature and precipitation rates at LGM were decreased by 3.13 K and 0.35 mm/day respectively. The land temperature dropped by 5.13 K in the northern hemisphere and by 1.13 K in the southern hemisphere. The 130 m sea level drop increased the continental area by 23 millions km$^2$. The high latitudes were most influenced by the LGM conditions as far as temperature is concerned. The decrease in precipitation over land affected mostly South America, Africa and Australia. The modeled temperature and precipitation fields were then used to calculate the biotemperature and annual precipitation distributions. These two fields, simulated at a 10°× 10° resolution, were linearly interpolated on a 5°× 5° grid and applied to the bioclimatic scheme described before.

## Simulated glacial biosphere

Global maps of the simulated distribution of vegetation are presented in Figure 1. Following this simulation, the boreal vegetation types were shifted towards lower latitudes with tundra occupying areas presently covered by coniferous, and to a lesser extent, deciduous forests. This is basically a result of the reduced temperatures over these regions. Lower precipitation rates 18 kyr years ago in Australia and Sahel explain why deserts were more extensive and grasslands and shrublands less extensive. Decreased precipitation was also responsible for the reduction in seasonal tropical forests which are replaced by grasslands and shrublands in Southern Africa. However, seasonal tropical forests expanded on lands that are immersed today in South East Asia and Occania. Evergreen tropical forests were almost absent from the equatorial regions where they are to be found now. As evergreen tropical forests have high NPP, the reduction in their size has a strong negative effect on the total living phytomass at glacial time (Column 5, Table 2). Total living phytomass is also strongly dependent on the redistribution of coniferous forest and tundra, since the latter is much less carbon-productive than the former. On the other hand, additional phytomass (about 120 GtC) was present due to the

Table 2. Comparison of the extent (in $10^6$ km$^2$)and carbon content (in GtC) of the terrestrial biosphere for present natural and LGM conditions (Antarctica excluded).

| | Vegetation type | Area | | Phytomass | | Soil carbon | |
|---|---|---|---|---|---|---|---|
| | | Present | LGM | Present | LGM | Present | LGM |
| 1 | Perennial ice | 3 | 23 | 0 | 0 | 0 | 0 |
| 2 | Desert and semidesert | 16 | 24 | 1 | 1 | 31 | 34 |
| 3 | Tundra | 10 | 21 | 25 | 34 | 124 | 236 |
| 4 | Coniferous forest | 24 | 12 | 236 | 91 | 307 | 159 |
| 5 | Deciduous forest | 16 | 14 | 237 | 204 | 163 | 144 |
| 6 | Grassland and shrubland | 36 | 34 | 30 | 27 | 240 | 239 |
| 7 | Seasonal tropical forest | 20 | 25 | 225 | 276 | 236 | 312 |
| 8 | Evergreen tropical forest | 11 | 6 | 147 | 64 | 196 | 103 |
| | Total | 136 | 159 | 901 | 697 | 1297 | 1197 |

Table 3. Fractions of herbaceous and woody biomass and mean residence time by vegetation type (numbers refer to Table 2, Column 1).

| Vegetation type | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Herbaceous ratio | 1. | 1. | 0.155 | 0.0265 | 0.0265 | 1. | 0.0225 | 0.0225 |
| Woody ratio | 0. | 0. | 0.845 | 0.9735 | 0.9735 | 0. | 0.9775 | 0.9775 |
| Residence time in herbaceous biomass (in years) | 1.5 | 1. | 1.5 | 2. | 2. | 1. | 1. | 1. |
| Residence time in woody biomass (in years) | - | - | 50. | 60. | 60. | - | 30. | 30. |

larger land area resulting from the lower sea level. Altogether, the phytomass accumulated by the vegetation at LGM was 23 % lower than at present time. Soil organic carbon pool calculated as mentioned before does not present a significant difference between the present and glacial period (Column 7, Table 2).

## Discussion and conclusions

An interesting comparison is possible with the reconstruction by Adams et al. (1990). The general trends between the two approaches agree, showing an increase at LGM in the areas covered by low vegetation types and deserts at the expense of forests. The Adams et al. results are more drastic than those in our study: they estimated a relative change of -52 %, +20 % and +98 %, with Antarctica, ( to compare with -20 %, +20 % and +136 % in the present study, without Antarctica) for areas covered by forest, low vegetation types and deserts (Antarctica included), respectively. Due to this important shift from high to low carbon content vegetation types, the amount of terrestrial carbon at LGM is significantly smaller in their study. They estimated a total decrease of 1071 GtC (if wetlands and peatlands are not considered), whereas we modeled a smaller drop of 300 GtC (Figure 2). Reasons for this difference may probably be found in the simulated LGM climate, especially the precipitation field. Consistently with other atmospheric models (Rind, 1987), the simplified model used here seems to overestimate the amount of water available for vegetation. Particularly, precipitation rates seem to be too high in intra-tropical regions to cut off the forested areas as in the Adams's study. To test this assumption, the annual precipitation field at LGM,

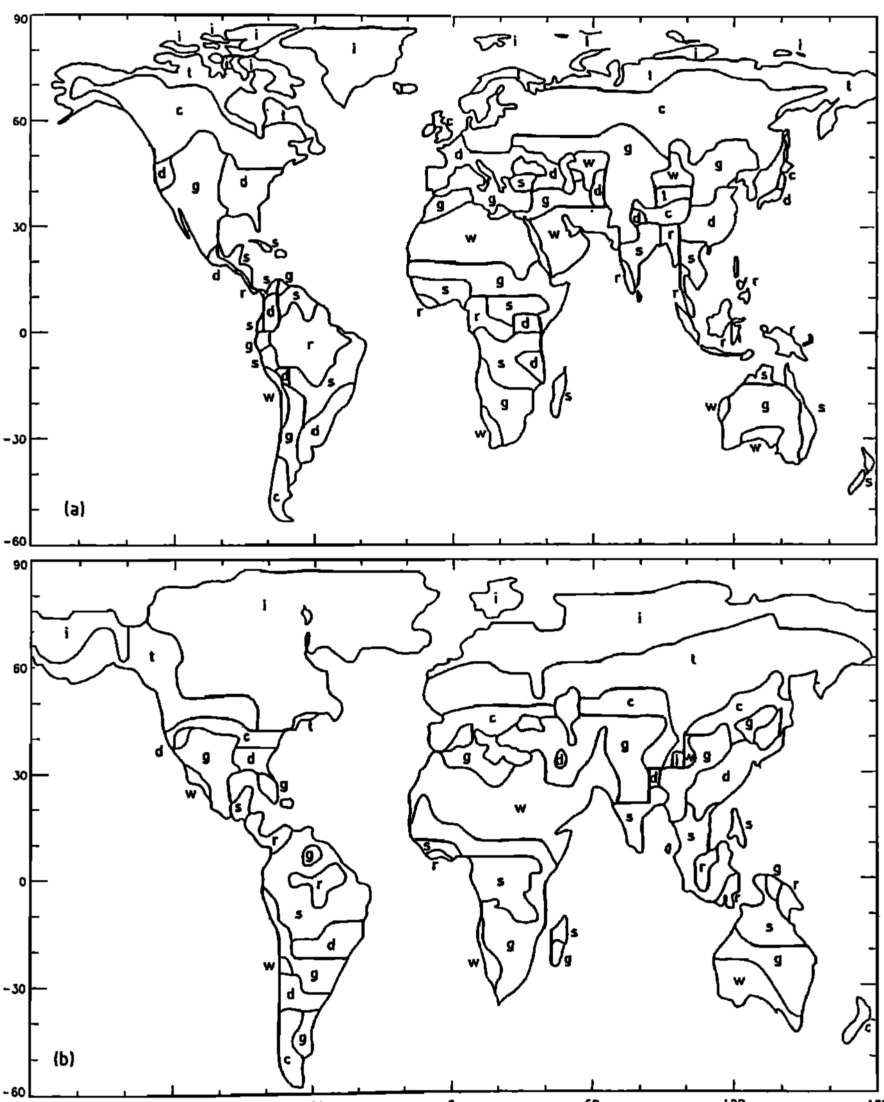


Fig. 1. (a). Simulated present day distribution of vegetation types: perennial ice [i], warm desert [w], grassland and shrubland [g], tundra [t], coniferous forest [c], deciduous forest [d], seasonal tropical forest [s] and evergreen tropical forest [r]. (b). Same for Last Glacial Maximum.

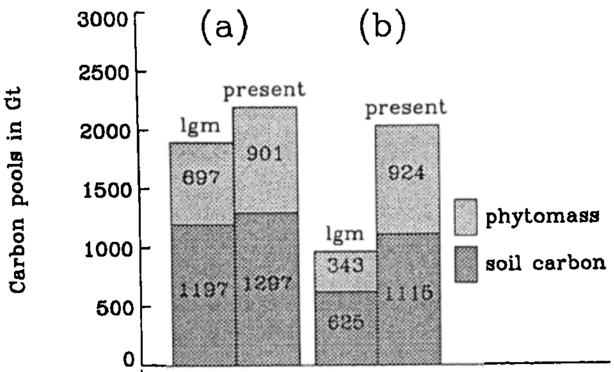


Fig. 2. Living phytomass and soil carbon content for present day and LGM conditions: (a) this work, (b) Adams et al. (1990) (without wetlands and peatlands).

estimated from January and July distributions simulated by the NCAR CCM0 (Kutzbach and Guetter, 1986), was applied to the bioclimatic scheme. The resulting distribution of vegetation is similar to the one obtained with the simplified GCM, except for the equatorial regions where the presence of evergreen tropical forest as extensive as today is simulated. This can be explained by the CCM0's steep gradient of the precipitation field between the tropics and the equator, allowing large tropical deserts neighbouring important moist climate types around the equator. Excessive precipitation rates may also account for the slightly larger carbon pool at LGM than today as estimated by Prentice and Fung (1990).

Another limitation of both our and Prentice and Fung's study results from the assumption that the bioclimatic scheme developed for present climate remains valid for LGM conditions, i.e. the hypothesis that precipitation and biotemperature are the dominant factors in the vegetation "struggle for life". Low atmospheric $CO_2$ content could further reduce the phytomass in a non negligible way. The productivity of the biosphere and hence the phytomass and the soil carbon at the LGM would be reduced by a factor of about two if the parameterization of the Osnabrück model (Esser, 1987) was used to take into account the "defertilization" $CO_2$ effect. Moreover, the bioclimatic scheme assumes that the vegetation distribution is in equilibrium with climate. Since the last glaciation lasted more than 10000 years, this equilibrium was probably reached. But this may not be the case when considering faster climate changes. Studies of the vegetation distribution of the next century require a dynamical model of vegetation including, among other factors, the role of soils.

Our results, i.e. a low biospheric carbon content at LGM, combined with the low atmospheric $CO_2$ concentration, suggest that the oceans should have played an important role in the carbon storage during the glacial to interglacial transitions, as also revealed by deep-sea core analysis (Shackleton, 1983).

*Acknowledgments.* We thank Pr. W. Sellers for his help in the use of the simplified Global Climate Model and P. Behling for providing outputs of the NCAR CCM0 runs for LGM conditions. Useful discussions with, G. Brasseur, D. Erickson, H. Faure, B. Holland and R. Keeling are gratefully acknowledged. The authors are grateful to the Belgian Institute for Encouragement of Industrial and Agricultural Scientific Research (IRSIA) (PF and CD) and the Belgian Fund for Scientific Research (FNRS) (JFM and JCG) for financial support. Part of this work was supported by the Belgian National Impulse Programmes "Global Change" and "Information Technologies - Supercomputing" of the Belgian State - Prime Minister's Service - Science Policy Office.

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P. Friedlingstein and J.F. Müller, Institut d'Aéronomie Spatiale, 3, avenue circulaire B-1180 Bruxelles -Belgium

C. Delire and J.C. Gérard, Institut d'Astrophysique, Université de Liège, 5, avenue de Cointe B-4000 Liège - Belgium.

(received : January 20, 1992;
revised : March 4, 1992;
accepted : March 4, 1992.)