INFLUENCE OF THE CLIMAP ICE SHEET ON THE CLIMATE OF A GENERAL CIRCULATION MODEL : IMPLICATIONS FOR THE MILANKOVITCH THEORY

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INTRODUCTION

While the spectral analysis of data from deep sea cores supports the suggestion that the temporal variation of the earth's orbital parameters is responsible for triggering the growth and decay of continental ice during the Quaternary (1), the physical factors responsible for maintaining a global ice age climate are less well understood. One of the important factors in maintaining a lowered atmospheric temperature during an ice age is the presence of large continental ice sheets that reflect a large fraction of incoming solar radiation. This study investigates the influence of the 18 kyr BP (18 000 years before present) ice sheet on the earth's climate by use of a mathematical model of climate constructed at the Geophysical Fluid Dynamics Laboratory of NOAA.

As the box diagram of Figure 1 indicates, the mathematical model used for this study consists of three basic units : 1) a general circulation model of the atmosphere, 2) a heat and water balance model over the continents, and 3) a simple model of the oceanic mixed layer. A brief description of these three units follows. A more detailed description of this atmosphere-mixed layer ocean model can be found in Manabe and Stouffer (2).

The atmospheric general circulation model computes the rates of change with time of the vertical component of vorticity, horizontal divergence, temperature, moisture, and surface pressure using the so-called "spectral method". The dynamical component of this model is developed by Gordon and Stern (3). Manabe et al. (4) and Manabe and Hahn (5) discuss

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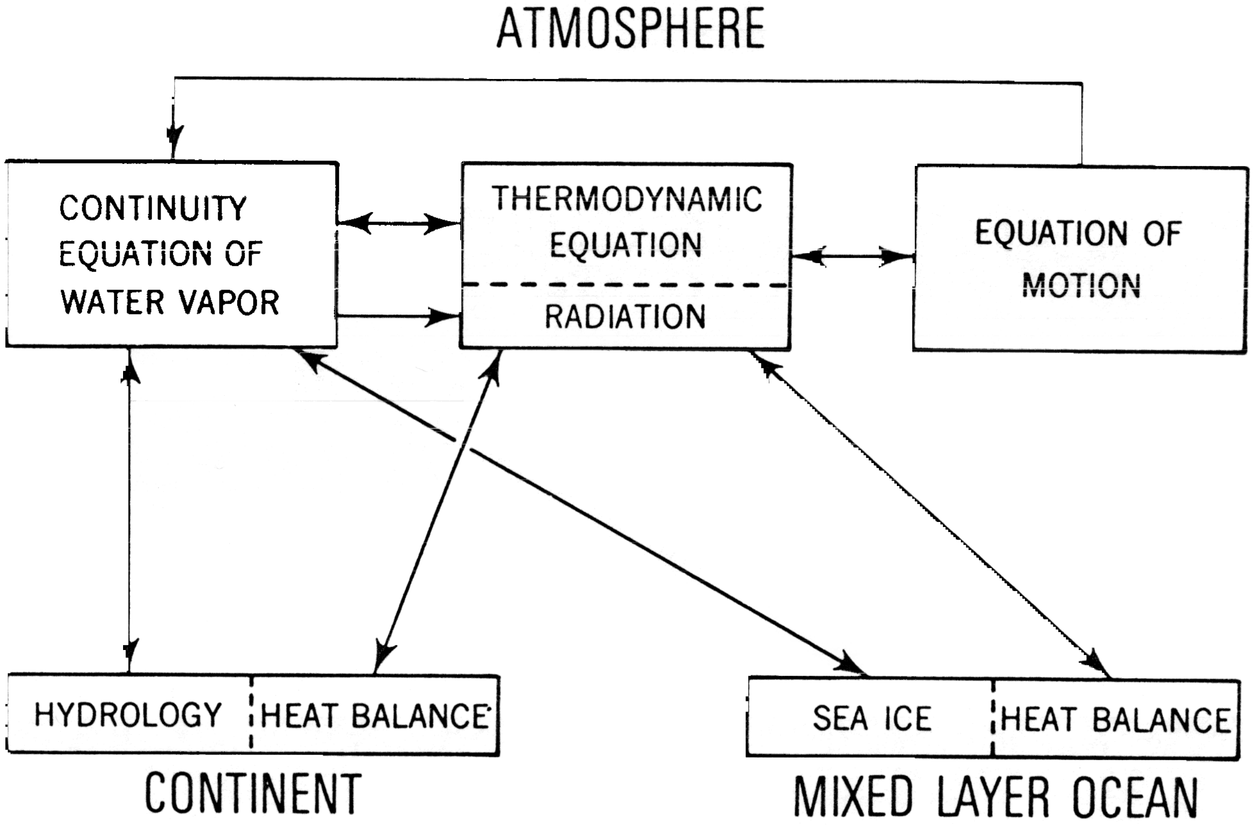


Figure 1 Box diagram illustrating the basic structure of the mathematical model of climate.

the structure and performance of this atmospheric model in detail.

Over the continents, the assumption of zero surface heat storage is used to determine surface temperatures from energy fluxes at the surface. Snow is allowed to accumulate on the surface, with the change in snow depth predicted as the net contribution from snowfall, sublimation, and snowmelt. A higher surface albedo is used when snow is present. Also used is a water balance model which computes changes in soil moisture from the rates of rainfall, evaporation, snowmelt and runoff. Further details of the hydrologic computations can be found in Manabe (6).

The oceanic mixed layer model consists of a vertically isothermal layer of static water of uniform depth. This model includes the effects of oceanic evaporation and the large heat capacity of the oceanic mixed layer, but neglects the effects of horizontal heat transport by ocean currents and of the heat exchange between the mixed layer and the deeper parts of the ocean. Sea ice is predicted when the mixed layer temperature falls below the freezing point of sea water (-2°C), and a higher surface albedo is used where sea ice is present.

EXPERIMENTAL DESIGN

In order to investigate the influence of continental ice sheets on the climate of an ice age, two long term integrations of the atmosphere-mixed layer ocean model described in the preceding section are conducted. The first time-integration, hereafter identified as the standard experiment, assumes as a boundary condition the modern distribution of continental ice. The second time-integration assumes the distribution of continental ice at the time of the last glacial maximum as reconstructed by CLIMAP (7), and will hereafter be identified as the ice sheet experiment.

A sea level difference between the two experiments of 150 m is prescribed, consistent with the glacial lowering of sea level as estimated by CLIMAP. Orbital parameters in both experiments are set at modern values, making the distribution of insolation at the top of the atmosphere with latitude and season the same in both experiments. This simplification is reasonable, since the orbital parameters at 18 kyr BP are not very different from the modern values. The surface albedo distribution of snow- and ice-free areas is prescribed to be the same in both experiments.

The initial condition for both time integrations is a dry, isothermal atmosphere at rest coupled with an isothermal mixed layer ocean. In both cases, the model is time integrated for 20 seasonal cycles. A quasi-equilibrium model climate is achieved after 15 model years, and the subsequent five-year period is used for analysis in each experiment.

In Figure 2, the geographical distribution of February surface air temperature of the model atmosphere is compared with the surface distribution compiled by Crutcher and Meserve (8) and Taljaad et al. (9). This comparison indicates that, despite some exceptions, the model succeeds in reproducing the general characteristics of the observed distribution of surface air temperature. The success of the model in simulating the geographical distribution of climate and its seasonal variation encouraged the authors to conduct the present study by use of this model.

THERMAL RESPONSE

Sea Surface Temperature

To illustrate the effect of continental ice on the distribution of sea surface temperature (SST), Figures 3 and 4 are constructed. These figures show the geographical distributions of the SST difference of the model mixed layer ocean between the ice age and standard experiments for February and August, respectively. These can be compared to the distributions of SST difference between 18 kyr BP and the present as determined by CLIMAP, which are added to the lower half of each figure.

In the Northern Hemisphere in both winter and summer, SSTs from the ice sheet experiment are significantly lower than the corresponding temperatures in the standard experiment. The SST differences are most pronounced in the mid-latitudes of the North Atlantic and the North Pacific, with the ice sheet-induced cooling over the Atlantic generally larger than the corresponding cooling over the Pacific. This is in good qualitative agreement with the difference between the modern and 18 kyr BP distributions of SST as obtained by CLIMAP.

In contrast, the SST differences in the Southern Hemisphere of the model are very small in both seasons, while the SST differences as estimated by CLIMAP are of significant magnitude. Since most of the changes in the distribution of continental ice between the two experiments are located in the Northern Hemisphere, this result suggests that the presence of an ice sheet in one hemisphere has relatively little influence on the distribution of sea surface temperature in the other hemisphere.

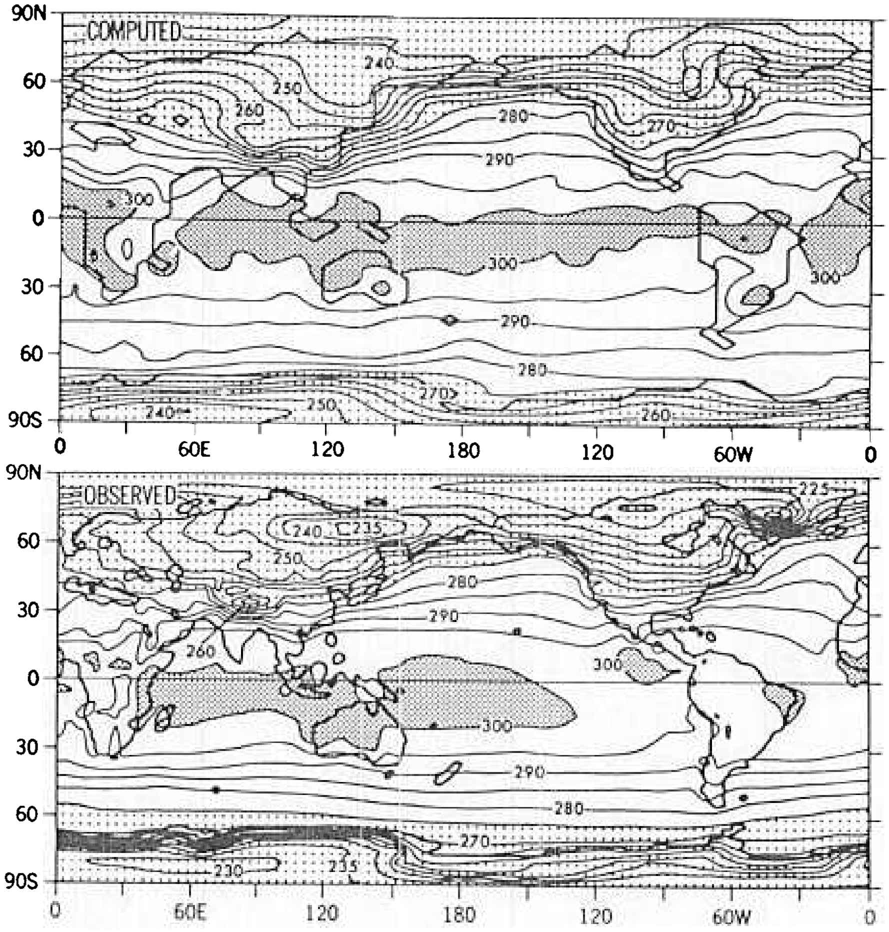


Figure 2 Geographical distributions of monthly mean surface air temperature (degrees Kelvin) in February. Top : computed distribution from the standard experiment. Bottom : observed disitribution (8,9). The computed surface air temperature represents the temperature of the model atmosphere at the lowest finite difference level located at about 70 m above the earth's surface.

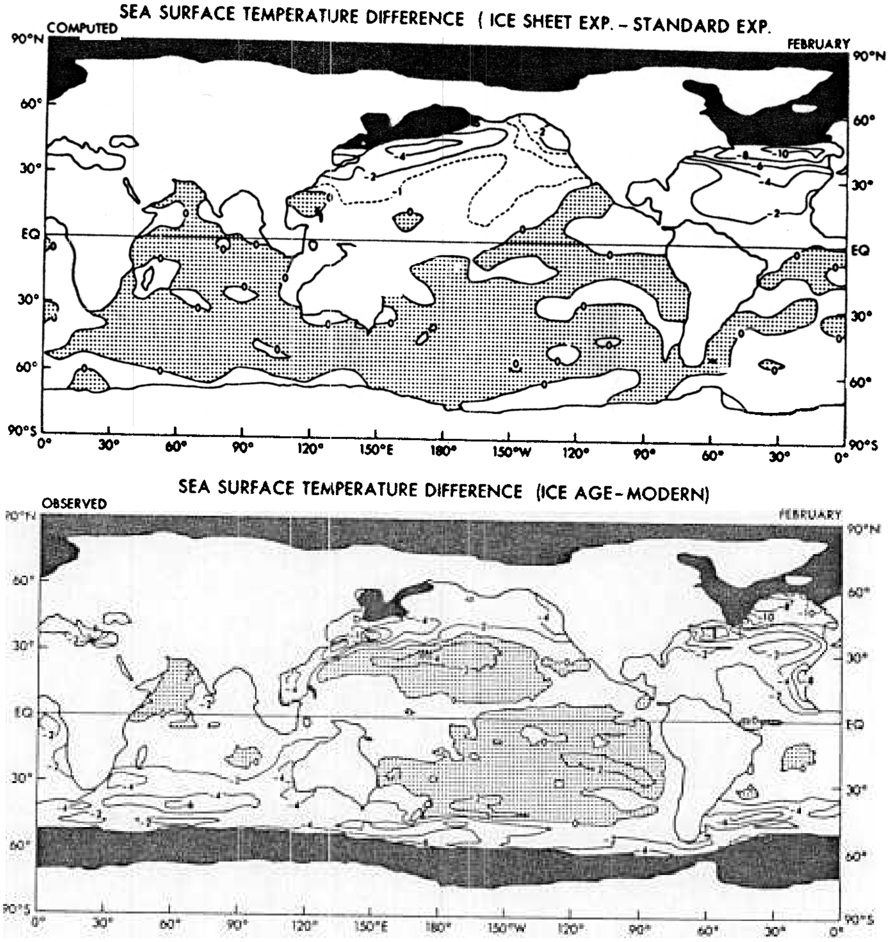


Figure 3 Geographical distribution of February sea surface temperature differences (degrees Kelvin). Top : difference between ice sheet and standard experiments. Bottom : difference between 18 kyr BP and present (as reconstructed by CLIMAP).

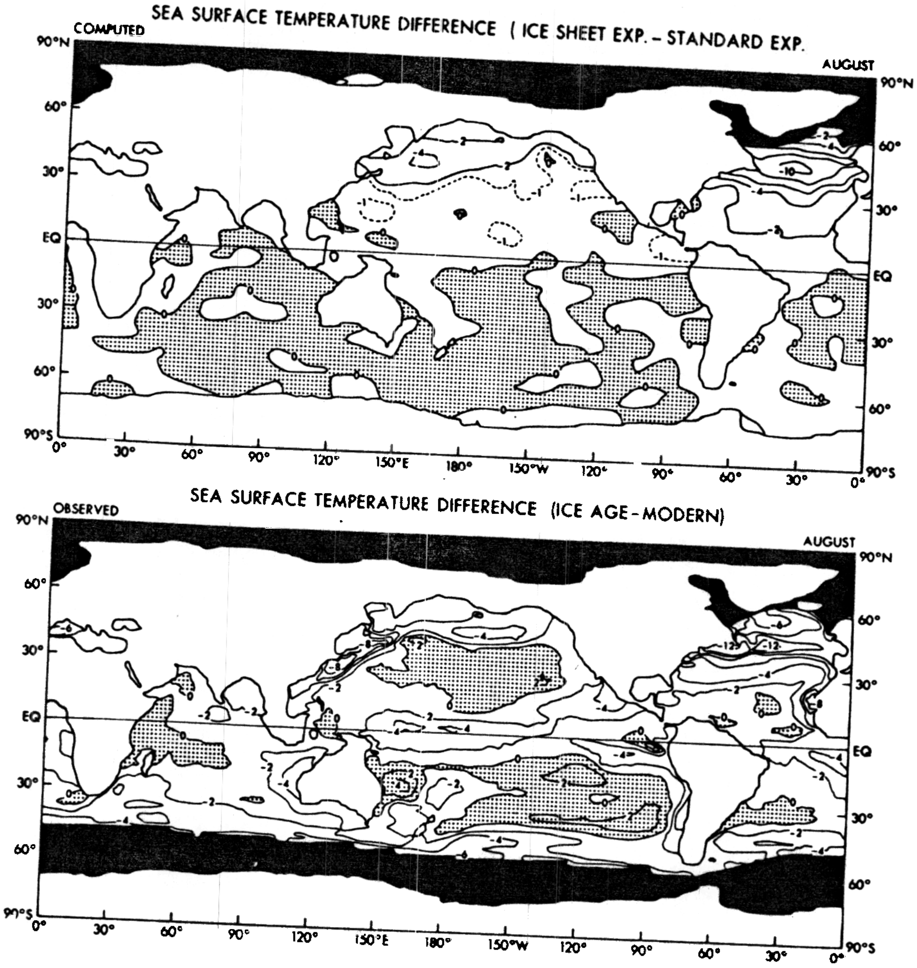


Figure 4 Same as Figure 3 except for August.

Hemispheric Heat Balance

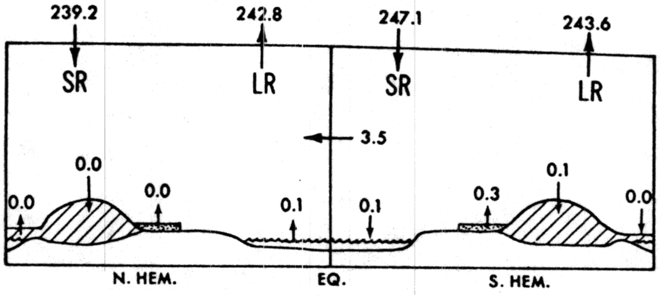
To evaluate the lack of a Southern Hemisphere response to the presence of widespread continental ice in the Northern Hemisphere, the hemispheric heat budgets of the model atmosphere are obtained from the standard and ice sheet experiments. These are illustrated by the box diagrams in Figure 5, as is the difference in heat budget between the two experiments.

For the Northern Hemisphere, the net downward flux of solar radiation at the top of the model atmosphere in the ice sheet experiment is 5.6 W m^{-2} less than the corresponding flux in the standard experiment. This is primarily due to the reflection of insolation by the large area of continental ice. The difference in incoming solar radiation is essentially counterbalanced by a difference of 5.8 W m^{-2} in outgoing terrestrial radiation at the top of the model atmosphere. Although the rate of interhemispheric heat exchange is also different between the two experiments, the magnitude of the difference is only 0.4 W m^{-2}, and is much smaller than the differences in the net incoming solar radiation and net outgoing terrestrial radiation.

These results indicate that, in the ice sheet experiment, the effective reflection of incoming solar radiation reduces the surface and atmospheric temperatures in the Northern Hemisphere of the model[1] and, accordingly, the outgoing terrestrial radiation at the top of the atmosphere (10). The relatively low surface temperature in the Northern Hemisphere induces a small increase in the heat supplied from the warmer atmosphere in the Southern Hemisphere. However, the radiative compensation in the Northern Hemisphere is much more effective than the thermal adjustment through the interhemispheric heat exchange in the model atmosphere.

CONCLUSIONS

The results of this study suggest that the effects of increased continental ice extent alone are insufficient to explain the glacial climate of the Southern Hemisphere, although variations in the earth's orbital parameters may be responsible for including the large fluctuations in the extent of Northern Hemisphere ice sheets during the Quaternary. Thus it is necessary to look for mechanisms other than the interhemispheric exchange of heat in the atmosphere in order to explain the low temperature of the Southern Hemisphere during the 18 kyr BP ice age. This is consistent with the results of Suarez and Held (11) using a simple energy balance model to study the astronomical theory of the ice ages.



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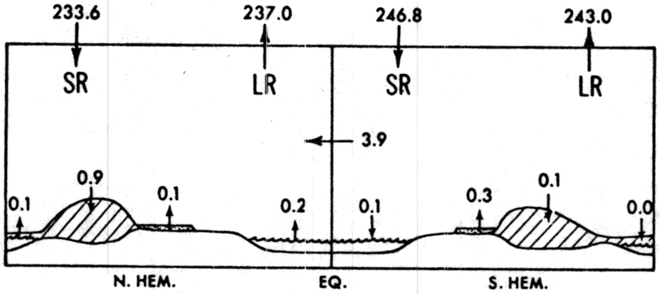
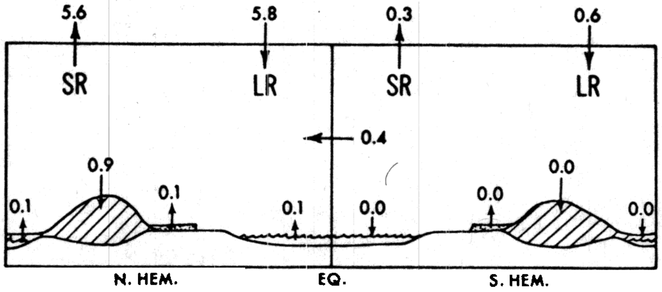


ICE SHEET



DIFFERENCE

Figure 5 Box diagrams representing the primary energy fluxes in the atmosphere-ocean-cryosphere system of the model. The surface fluxes shown at the bottom of the Northern Hemisphere box represent the heat energy involved in the growth and decay of sea ice, land ice, and permanent snowcover, and long-term changes in heat storage in the oceanic mixed layer. Top : standard experiment. Center : ice sheet experiment. Bottom : difference between ice sheet and standard experiments.

Among the potential mechanisms for the cooling of the Southern Hemisphere during glacial times is the cross-equatorial heat transport by the ocean circulation. For example, if the intensity of the interhemispheric thermohaline circulation changes from a glacial to an interglacial period, as is suggested by Rooth (12), it is possible that the interhemispheric ocean heat transport does also, resulting in a change of Southern Hemisphere temperature.

Other processes which can cause an almost simultaneous change of temperature in both hemispheres are fluctuations in the concentration of carbon dioxide of the loading of aerosols in the atmosphere. Indeed, the results from the recent analysis of ice cores from the Antarctic and Greenland ice sheets suggest that the atmospheric concentration of CO_2 during the last glacial maximum was about 200 ppm by volume and is significantly less than the current concentration of 340 ppm (13,14). Broecker (15) proposes a mechanism by which a reduction of atmospheric carbon dioxide might result from the lowering of sea level associated with the growth of continental ice. If such reduction did occur, it could account for much of the Southern Hemisphere cooling indicated in the CLIMAP results.

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[1] Strickly speaking, the ice sheet-induced reduction of surface temperature results not only from the large surface reflectivity but also from the high elevation of the ice sheet surface.