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ICE-AGE CLIMATE AND CONTINENTAL ICE SHEETS: SOME EXPERIMENTS WITH A GENERAL CIRCULATION MODEL

by

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ABSTRACT

The climatic influence of the land ice which existed 18 ka BP is investigated using a climate model developed at the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration. The model consists of an atmospheric general circulation model coupled with a static mixed layer ocean model. Simulated climates are obtained from each of two versions of the model: one with the land-ice distribution of the present and the other with that of 18 ka BP.

In the northern hemisphere, the difference in the distribution of sea surface temperature (SST) between the two experiments resembles the difference between the SST at 18 ka BP and at present as estimated by CLIMAP Project Members (1981). In the northern hemisphere a substantial lowering of air temperature also occurs in winter, with a less pronounced cooling during summer. The mid-tropospheric flow field is influenced by the Laurentide ice sheet and features a split jet stream straddling the ice sheet and a long wave trough along the east coast of North America. In the southern hemisphere of 18 ka BP, the ice sheet has little influence on temperature. An examination of hemispheric heat balances indicates that this is because only a small change in interhemispheric heat transport exists, as the in situ radiative compensation in the northern hemisphere counterbalances the effective reflection of solar radiation by continental ice sheets.

Hydrologic changes in the model climate are also found, with statistically significant decreases in soil moisture occurring in a zone located to the south of the ice sheets in North America and Eurasia. These findings are consistent with some geological evidence of regionally drier climates from the last glacial maximum.

1. INTRODUCTION

One of the main objectives of this study is to investigate how the cold climate of an ice age is maintained. In particular, this study attempts to identify the physical factors which are responsible for making the climate of the last major ice age much colder than the modern climate. Such physical factors may include (1) the existence of massive continental ice sheets which reflect a large fraction of insolation, (2) lower concentration of carbon dioxide in the atmosphere, (3) higher surface albedo of more arid continents, and (4) differences in the orbital parameters of the Earth.

Many studies have suggested that the temporal variation of the orbital parameters of the Earth is responsible for the transition between nonglacial and glacial climates. However, the values of the orbital parameters at the peak of the last major glaciation approximately 18 ka BP are similar to the modern values. Therefore, it is not likely that they were responsible for maintaining the cold ice-age climate, even though they may have triggered it. On the other hand, it is probable that the reflection of a large fraction of insolation by continental ice sheets was important in maintaining an ice-age climate. Primarily for this reason, the climatic influence of continental ice sheets is chosen as the subject for the present study.

To investigate this influence, a coupled atmosphere/mixed layer ocean model developed by Manabe and Stouffer (1980) is used. In this model, sea surface temperature (SST) is a predicted quantity, so the influence of continental ice sheets not only on the atmospheric circulation but also on SST can be investigated. For this reason, the study is fundamentally different from those of Gates (1976[a],[b]), Manabe and Hahn (1977), and Kutzbach and Guetter (1984), which used ice-age SSTs reconstructed by CLIMAP Pro-

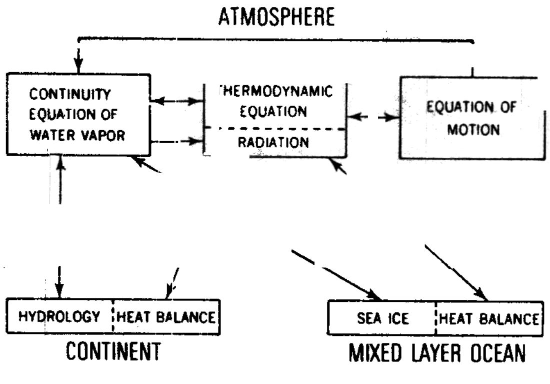

Fig.1. Box diagram illustrating the basic structure of the coupled atmosphere/mixed layer ocean climate model.

ject Members (1981) as a prescribed lower boundary condition for their models.

2. MODEL STRUCTURE

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 (1980).

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 (1982). Manabe and others (1979) and Manabe and Hahn (1981) discuss 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 snow-melt. 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, snow-melt and run-off. Further details of the hydrologic computations can be found in Manabe (1969).

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 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 temperature of the mixed layer falls below the freezing point of sea-water (-2°C), and a higher surface albedo is used where sea ice is present. The distribution and thickness of continental ice is prescribed at the start of an experiment and does not change during its course, but ablation and accretion rates are computed.

Manabe and Stouffer (1980) compared the geographical distribution of climate from this model with observed climatic data. They found that, despite some exceptions, the model succeeds in reproducing the general characteristics of the observed distribution of surface air temperature and precipitation. 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.

3. EXPERIMENTAL DESIGN

In order to investigate the influence of continental ice sheets on the climate of an ice age, two

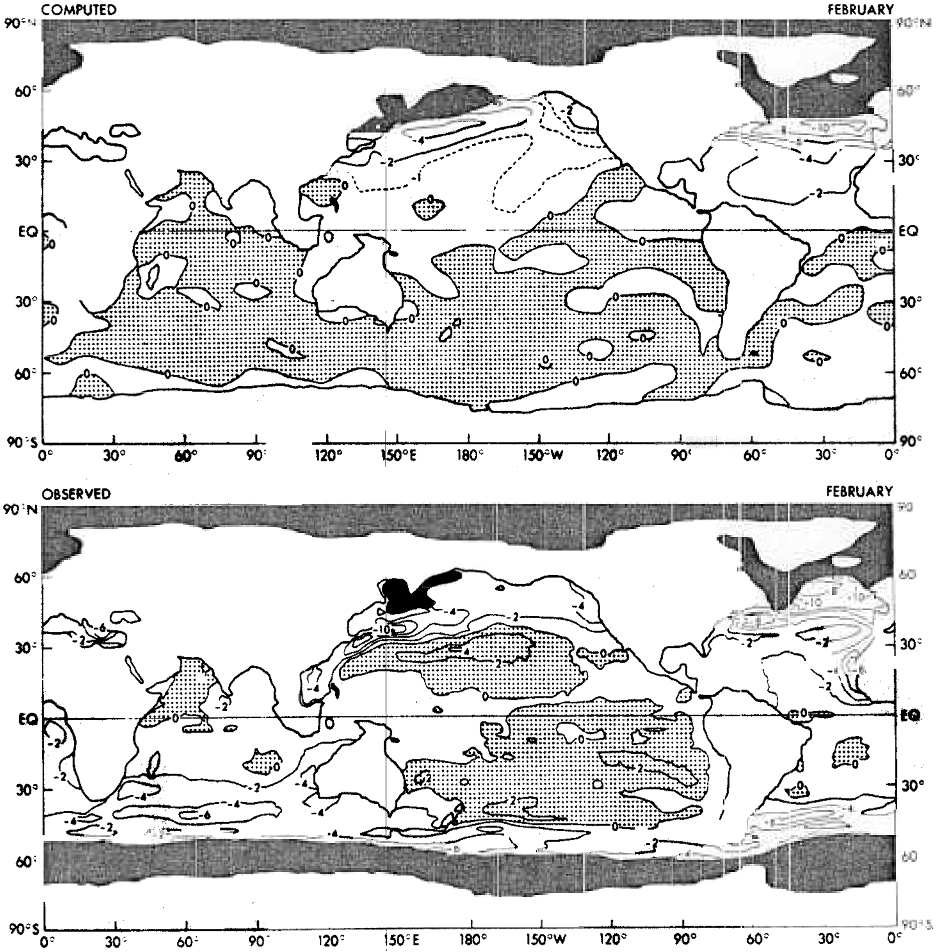

Fig.2. February monthly mean SST difference (degrees Kelvin, stippling indicates positive difference). Top: difference between ice-sheet and standard experiments. Bottom: difference between 18 ka BP and present (as reconstructed by CLIMAP Project Members 1981). Areas covered by sea ice in the ice-sheet experiment and at 18 ka BP are indicated by black shading.

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 Project Members (1981) and will hereafter be identified as the ice-sheet experiment.

A difference in sea-level between the two experiments of 150 m is prescribed, consistent with the glacial lowering of sea-level as estimated by the Climate: Long-range Interpretation, Mapping and Prediction (CLIMAP) project. 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 ka BP are not very different from the modern values. The distribution of the surface albedos 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.

4. CLIMATIC RESPONSE

4(a). Sea surface temperature

To illustrate the effect of continental ice on the distribution of SST, Figure 2 is constructed. This figure shows, as an example, the geographical distributions of the SST difference of the model mixed layer ocean between the ice-sheet and standard experiments for February. This can be compared to the distribution of SST difference between 18 ka BP and the present as determined by CLIMAP Project Members (1981), which is added to the lower half of the figure.

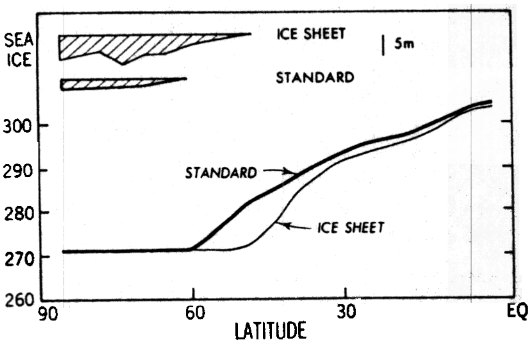

Fig.3. Winter (DJF) zonal mean SST (degrees Kelvin) and sea-ice thickness (scale represents 5 m) for the North Atlantic Ocean from the standard and ice-sheet experiments.

In the northern hemisphere, 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 cooling over the Atlantic generally larger than that over the Pacific. This is in good qualitative agreement with the difference between the distributions of SST now and in 18 ka BP obtained by CLIMAP Project Members (1981).

In contrast, the SST differences in the southern hemisphere of the model are very small, whereas the SST differences as estimated by CLIMAP are of significant magnitude. As most 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 SST in the other hemisphere.

It is significant that, in winter, the SST difference is largest in the mid-latitudes of the North Atlantic and North Pacific oceans. This is near the southern margin of the extensive sea ice which is present in the ice-sheet experiment. One can appreciate the reason for this location by consulting Figure 3 which shows the latitudinal distributions of zonal mean SST over the North Atlantic Ocean for winter obtained from both experiments. As this figure indicates, SST always remains at the freezing point (i.e. -2°C) beneath sea ice and increases equatorward of the sea-ice margin in both experiments. It is, therefore, reasonable that the SST difference is largest in the neighborhood of the sea-ice margin in the ice-sheet experiment.

4(b). Atmospheric circulation

In the preceding subsection, it is shown that the extensive sea ice which forms in the North Atlantic Ocean exerts a strong influence upon the distribution of SST in the ice-sheet experiment. Some of the key processes responsible for the formation of this sea ice may be identified based upon the analysis of the atmospheric circulation obtained from the ice-sheet experiment.

Figure 4 contains the December-January-February (DJF) map of the geopotential height at 500 mbar which is obtained from the ice-sheet experiment. From this map, one can infer the flow field at 500 mbar level of the model atmosphere with the aid

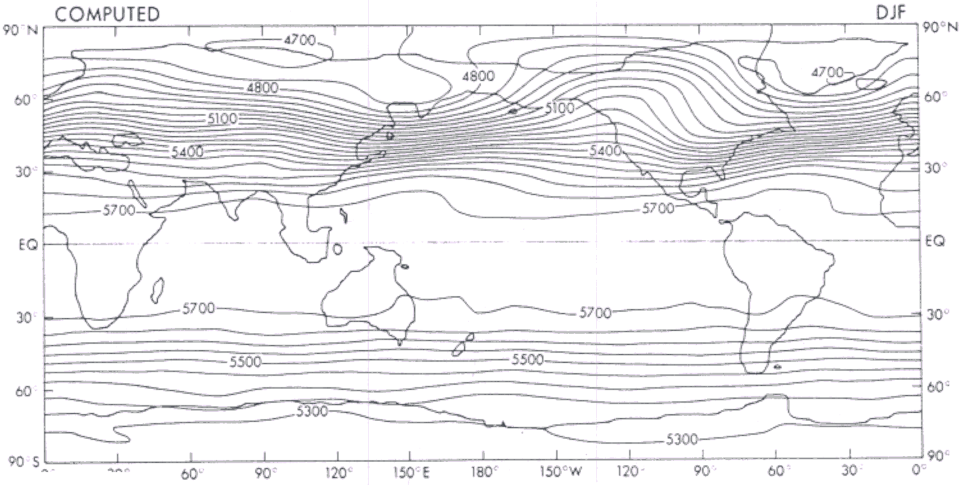

Fig.4. Winter (DJF) 500 mbar geopotential height (m) from the ice-sheet experiment.

of the geostrophic relationship. According to this figure, the mid-tropospheric flow field in the ice-sheet experiment is characterized by (1) the double jet streams straddling the Laurentide ice sheet and (2) a planetary wave trough along the east coast of the North American continent. Along the southern branch of the jet located near the southern boundary of the ice sheet, cyclone waves propagate eastward inducing intense snowfall. Under the northern jet, cold air flows around the northern periphery of the Laurentide and the Greenland ice sheets, eventually reaching the surface of the North Atlantic Ocean.

This is clearly illustrated in Figure 5 which contains the map of surface streamlines for the DJF season from the ice-sheet experiment. By the time this air mass reaches the North Atlantic Ocean, it is extremely cold and is responsible for the formation of the thick sea ice over the model ocean. This is implied in the upper portion of Figure 6, which illustrates the distribution of the difference

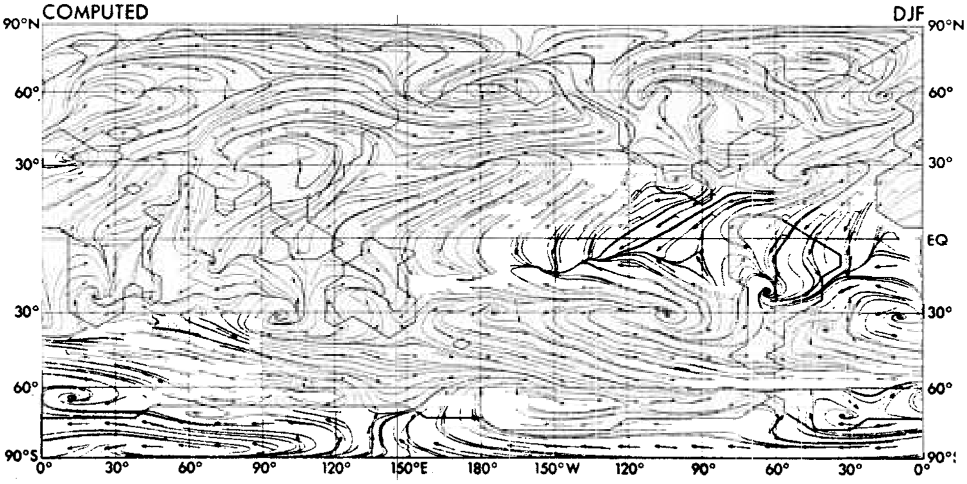

Fig.5. Winter surface wind vectors and streamlines from the ice-sheet experiment. (Each full wind barb represents 5 m s^{-1}.)

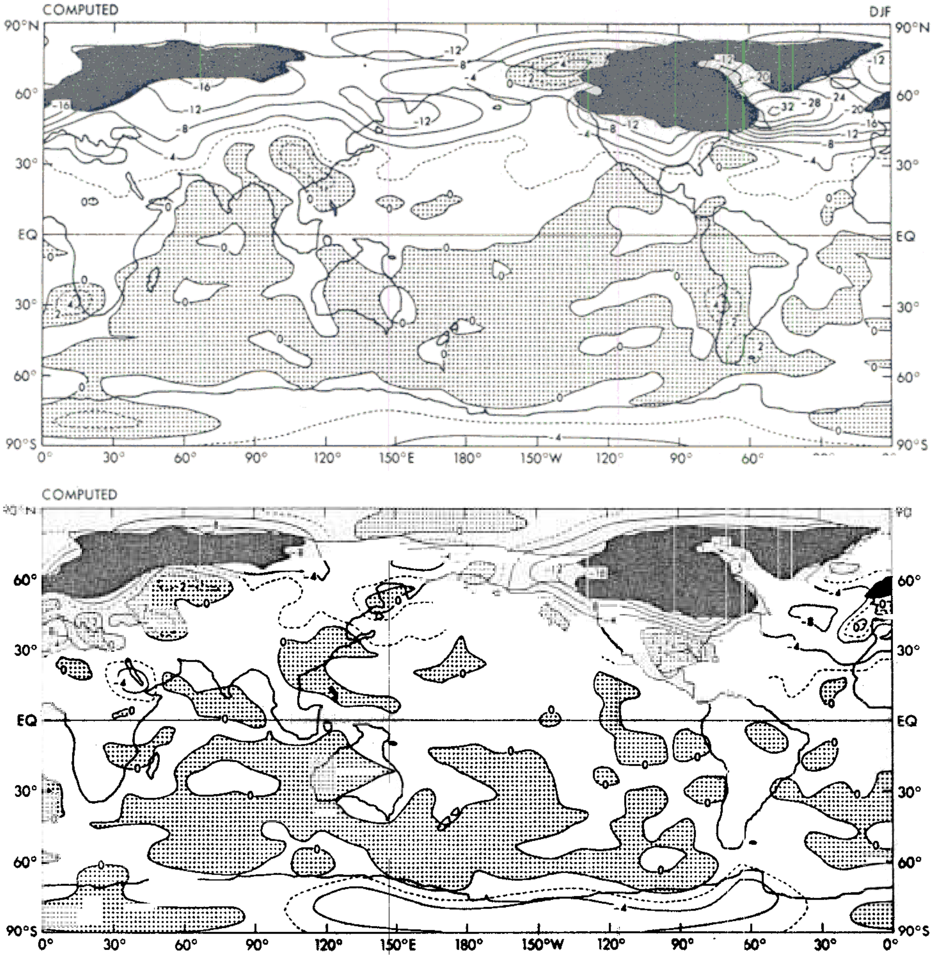

Fig.6. Difference in surface air temperature between the two experiments (degrees Kelvin, stippling indicates positive difference). Top: DJF. Bottom: JJA.

in surface air temperature between the ice sheet and the standard experiments. As can be noted by comparing this figure and Figure 2, the difference in surface air temperature between the two experiments over the North Atlantic Ocean is much larger than the corresponding difference in sea surface temperature owing to the thermal insulation by sea ice. The intense outflow of cold air described above partly explains why the difference in surface air temperature over the North Atlantic Ocean between the two experiments is significantly larger than the corresponding difference over the North Pacific in winter.

Over the continents in the northern hemisphere the February difference in surface air temperature between the two experiments is large, particularly near southern continental ice margins where cold katabatic winds blow southward from the massive ice sheets. In summer (June-July-August (JJA)), the difference in surface air temperature over the continents of the northern hemisphere is much smaller, as indicated in the lower half of Figure 6. One can even note isolated areas of positive difference where the ice-sheet experiment is simulated to be warmer than the standard experiment. These positive differences usually occur in the areas where the aridity of the soil increases from the standard to the ice-sheet experiments. This topic is the subject of the discussion in a subsequent subsection.

The smallness of the difference in summer temperature described above is not consistent with the recent compilation of paleoclimatic data from 18 ka BP by Peterson and others (1979), which indicates larger differences in temperature between 18 ka BP and the present during all seasons. It may be necessary to include other factors such as the differences in surface albedo and atmospheric concentrations of carbon dioxide in climate models in order to reproduce cold surface air temperatures in summer over the continents in middle and high latitudes of the northern hemisphere.

Partly because of the warm continental air described above, very rapid melting is indicated at the southern periphery of both the Scandinavian and Laurentide ice sheets. It is found, however, that the rate of ablation of an ice sheet depends critically upon the specific values of some key parameters such as the surface albedo of melting ice and the fraction of meltwater which becomes run-off. Further studies are required before one can determine these parameters, and the factors which influence them, reliably.

4(c). Hemispheric heat balance

To evaluate the lack of response in the southern hemisphere 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. 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 in the northern hemisphere. Although the rate of interhemispheric heat exchange is also different in 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 in the northern hemisphere. In the southern hemisphere, there is little change in both the incoming solar radiation and the 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 and, accordingly, the outgoing terrestrial radiation at the top of the atmosphere. 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.

4(d). Hydrologic response

The geographical distribution of the percentage change in annual mean soil moisture between the two experiments is shown in Figure 7. As discussed in the figure caption, no contours are drawn in regions of increase in soil moisture. Large areas with a reduction of soil moisture in the ice-sheet experiment are evident south of the Laurentide and Scandinavian ice sheets. Tests for statistical significance of the difference in soil moisture at each gridpoint, using the method of Chervin and Schneider (1976), indicate that the differences in soil moisture are significant in a broad belt south of the ice sheet in the western Soviet Union and a smaller area in the Great Plains of North America.

The reduction of soil moisture in these regions is consistent with geological evidence of loess in both areas. One of the models for loess deposition (Smalley 1972) suggests that the particles are carried by the wind from the outwash of glacial sedi-

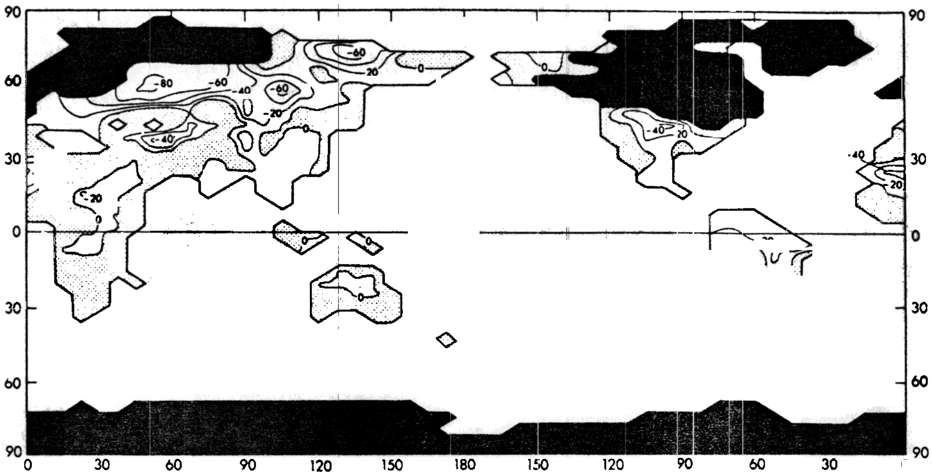

Fig.7. Percentage change in annual mean soil moisture from the standard to the ice-sheet experiment. Areas covered by continental ice are blacked out; stippling indicates areas with an increase of soil moisture. (Since the statistical significance of the change in soil moisture is small in regions of increase of soil moisture, no contours are drawn in these regions to

ments. Some have suggested that the existence of loess is indicative of a dry (or at least seasonally dry) climate during the time of its deposition.

An examination of the causes of the model reduction in soil moisture indicates that a reduction of precipitation is a primary factor. In North America, this reduction occurs primarily in summer and results from the small amount of moisture supplied to the atmosphere by sublimation from the cold Laurentide ice sheet. In Eurasia, similar processes also operate. In addition, the reduction in Eurasia during the warm season is related to the shift of the middle-latitude precipitation belt from a position several hundred kilometers south of the ice-sheet margin to a position along the ice-sheet margin. This shift is probably due to enhanced baroclinicity in this region resulting from the large contrast in surface temperature across the ice-sheet margin.

5. CONCLUSIONS

In this study, it was found that the distribution of continental ice, as modeled for 18 ka BP, exerts a major influence on the climate of a coupled atmosphere/mixed layer ocean model. Large reductions of SST in the northern hemisphere occur which are qualitatively similar to the SSTs for 18 ka BP which were reconstructed by CLIMAP Project Members (1981). A major reduction of surface air temperature in the northern hemisphere is also produced for the winter season, but is not present in summer.

In addition, the Laurentide ice sheet strongly influences the general circulation of the model atmosphere, particularly in winter, when a double jet stream forms which straddles the ice sheet. Under the northern jet stream, an extremely cold air mass flows along the northern periphery of the ice sheet, eventually reaching the North Atlantic Ocean and forming thick sea ice. Along the southern jet stream, cyclone waves propagate eastward and are responsible for intense snowfall prevailing along the southern boundary of the ice sheet. The role of this intense snowfall in the growth and maintenance of the ice sheet is the subject of future investigation.

It is of interest that both the Laurentide and Scandinavian ice sheets induce soil aridity in zonal belts located just to the south of the ice sheets. In particular, the simulated dry belt located to the south of the Scandinavian ice sheet is pronounced due to the poleward shift of the precipitation belt to the southern boundary of the ice sheet. It is desirable to perform further assessment of this result in the light of a wide variety of geological evidence.

The results of this study also suggest that the effects of the extent of the increased continental ice alone are insufficient to explain the glacial climate of the southern hemisphere, although variations in the Earth's orbital parameters may be responsible for inducing the large fluctuations in the extent of ice sheets in the northern hemisphere 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 in the southern hemisphere. This is consistent with the results of Suarez and Held (1982) using a simple energy balance model to study the astronomical theory of the ice ages.

Among the potential mechanisms for the cooling of the southern hemisphere during glacial times is a change in the cross-equatorial heat transport by the ocean circulation. Other processes which can cause an almost simultaneous change of temperature in both hemispheres are fluctuations in the concentration of carbon dioxide or 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 ppmv and is significantly less than the current concentration of 340 ppmv (Berner and others 1980, Delmas and others 1980, Stauffer and others 1984). If such a reduction did occur, it could account for much of the cooling of the southern hemisphere indicated in the CLIMAP results.

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