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THE EFFECTS OF THE LAURENTIDE ICE SHEET ON NORTH AMERICAN CLIMATE DURING THE LAST GLACIAL MAXIMUM

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ABSTRACT A climate model, consisting of an atmospheric general circulation model coupled with a simple model of the oceanic mixed layer, is used to investigate the effects of the continental ice distribution of the last glacial maximum (LGM) on North American climate. This model has previously been used to simulate the LGM climate, producing temperature changes reasonably in agreement with paleoclimatic data. The LGM distribution of continental ice according to the maximum reconstruction of HUGHES *et al.* (1981) is used as input to the model. In response to the incorporation of the expanded continental ice of the LGM, the model produces major changes in the climate of North America. The ice sheet exerts an orographic effect on the tropospheric flow, resulting in a splitting of the midlatitude westerlies in all seasons but summer. Winter temperatures are greatly reduced over a wide region south of the Laurentide ice sheet, although summer cooling is less extensive. An area of reduced soil moisture develops in the interior of North America just south of the ice margin. At the same time, precipitation increases in a belt extending from the extreme southeastern portion of the ice sheet eastward into the North Atlantic. Some of these findings are similar to paleoclimatic inferences based on geological evidence.

RÉSUMÉ *L'influence de la calotte glaciaire laurentidienne sur le climat en Amérique du Nord durant le dernier pléniglaciaire.* Un modèle climatique, composé d'un modèle de circulation atmosphérique général associé à un modèle simple de la couche océanique mixte, a servi à étudier l'influence de la répartition des glaciers continentaux sur le climat de l'Amérique du Nord au dernier pléniglaciaire. Ce modèle avait déjà servi pour simuler le climat au dernier pléniglaciaire; il a montré des changements de températures concordant assez bien avec les données paléoclimatiques. La répartition des glaces continentales pendant le pléniglaciaire selon l'hypothèse d'extension maximale de HUGHES *et al.* (1981) a servi à la modélisation. En réponse à l'incorporation des données de cette hypothèse, le modèle fait voir des changements majeurs dans le climat de l'Amérique du Nord. La présence de la calotte glaciaire fait ressortir l'influence de l'orographie sur le flux troposphérique qui se concrétise par une séparation des vents d'ouest aux latitudes moyennes durant toutes les saisons, sauf l'été. Les températures hivernales s'abaissent substantiellement dans une vaste région située au sud de la calotte laurentidienne, bien que le refroidissement soit moindre durant l'été. Une zone sèche se développe immédiatement au sud de la marge glaciaire. Au même moment, les précipitations augmentent dans la région qui s'étend de l'extrémité sud-est de la calotte glaciaire jusque dans l'Atlantique Nord, à l'est. Certains de ces résultats sur la nature du paléoclimat sont similaires aux déductions que les données géologiques ont inspirées.

ZUSAMMENFASSUNG *Auswirkungen der laurentischen Eisdecke auf das Klima Nordamrikas während des jüngsten glazialen Maximums.* Um die Auswirkungen der kontinentalen Eisverbreitung im jüngsten glazialen Maximum auf das nordamerikanische Klima zu erforschen, wird ein Klima-Modell benutzt, das aus einem Modell der Hauptluftströmung in Verbindung mit einem einfachen Modell der gemischten ozeanischen Schicht besteht. Früher wurde dieses Modell benutzt, um das Klima im jüngsten glazialen Maximum zu simulieren. Die Ergebnisse haben Temperaturschwankungen ergeben, die einigermaβen genau mit den paleoklimatischen Daten übereinstimmten. Ausgegangen wurde bei dem Modell von der Verteilung des kontinentalen Eises im jüngsten glazialen Maximum entsprechend der Maximum-Rekonstruktion von HUGHES *et al.* (1981). Als Antwort auf die Einverleibung des ausgedehnten kontinentalen Eises im jüngsten glazialen Maximum produziert das Modell bedeutende Veränderungen im nordamerikanischen Klima. Die Eisdecke übt eine orographische Wirkung auf die troposphärische Luftströmung aus, was zu einer Aufsplitterung der westlichen Winde mittlerer Breite in allen Jahreszeiten auβer im Sommer führt. Die Winter-Temperaturen sinken stark in einem weiten Gebiet südlich der laurentischen Eisdecke, während die sommerliche Abkühlung weniger stark ausfällt. Im Innern Nordamerikas südlich der Eisgrenze entwickelt sich ein Gebiet verringerter Bodenfeuchtigkeit. Gleichzeitig nehmen die Niederschläge innerhalb eines Gürtels zu, der von dem äuβersten südöstlichen Teil der Eisdecke ostwärts in den Nordatlantik reicht. Einige dieser Ergebnisse decken sich mit paleoklimatischen Folgerungen, die sich auf geologische Nachweise stützen.

INTRODUCTION

In an effort to understand the dramatic changes in climate that occurred during the Pleistocene, a number of studies have been conducted using general circulation models to simulate the ice age climate. These studies were made possible by the comprehensive reconstruction of the surface characteristics of the earth during the last glacial maximum (LGM) by the CLIMAP Project (CLIMAP Project Members, 1976, 1981). This reconstruction of surface elevation, continental ice distribution, sea level, land surface albedo, and sea surface temperature (SST) was the first quantitative, global data set suitable for use as input to atmospheric general circulation models. GATES (1976a, b), MANABE and HAHN (1977), and HANSEN *et al.* (1984) used the CLIMAP surface reconstructions as input to such climate models in an effort to simulate the ice age climate.

Employing a slightly different approach, MANABE and BROCCOLI (1985a) used an atmospheric general circulation model coupled with a simple model of the oceanic mixed layer to study the influence of continental ice on the LGM climate. Unlike the models used in the studies cited previously, in which SST was prescribed, Manabe and Broccoli's model predicted SST. This allowed a comparison to be made between the changes in SST produced by their model and those reconstructed by CLIMAP. They found that the LGM distribution of continental ice produced changes in model SST similar to those reconstructed by CLIMAP in the Northern Hemisphere but, unlike the reconstruction, there was almost no change in Southern Hemisphere temperature. The tropospheric flow field was substantially altered, and a decrease in soil moisture occurred in areas just south of the ice sheets in North America and Eurasia.

The sensitivity of a similar model to ice age boundary conditions was examined by MANABE and BROCCOLI (1985b). They simulated the LGM climate using as input the expanded LGM continental ice, the reduced ice age atmospheric CO_2 concentration, and vegetation-induced changes in land surface albedo. The differences in SST and surface air temperature produced by the model were compared to paleoclimatic data from the LGM. Changes in model SST in response to LGM boundary conditions were reasonably similar to those reconstructed by CLIMAP, particularly outside the subtropics. Over land, the changes in surface air temperature were in good agreement with paleoclimatic data in the Northern Hemisphere extratropics, but were too small elsewhere. They concluded that the sensitivity of the model to LGM boundary conditions was realistic.

In a related study, BROCCOLI and MANABE (1987) used the same model to evaluate the relative strength of the contributions of expanded continental ice, reduced atmospheric CO_2, and changes in land surface albedo to the LGM climate. They found that the expansion of continental ice made the largest contribution to the cooling of the Northern Hemisphere, with little impact in the Southern Hemisphere. There, the reduction of atmospheric CO_2 was the most important cooling mechanism. Most of the substantial changes in atmospheric circulation in response to LGM boundary conditions were associated with the expanded continental ice.

In the current study, the model of BROCCOLI and MANABE (1987) is used to re-examine the influence of the LGM continental ice on climate. Since the model and the experimental design are very similar to those of MANABE and BROCCOLI (1985a), many of the results presented here are essentially the same as those presented in their paper. While their study discussed changes in climate from a global perspective, the current study, in keeping with the theme of the INQUA symposium, concentrates on the effects of continental ice on the North American climate. Substantial changes in temperature, soil moisture, precipitation, and tropospheric flow in response to the increased continental ice are identified and examined.

MODEL DESCRIPTION

As the box diagram of Figure 1 indicates, the mathematical climate 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.

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, in which these variables are represented by a limited number of spherical harmonics. The model's horizontal resolution is determined by the degree of truncation of the spectral components. For this study, 15 components are retained in both the zonal and meridional directions. This corresponds to a grid resolution of 4.5° latitude by 7.5° longitude. The dynamical component of this model is described by GORDON and STERN (1982). MANABE *et al.* (1979) and MANABE and HAHN (1981) discuss the structure and performance of this atmospheric model in more detail.

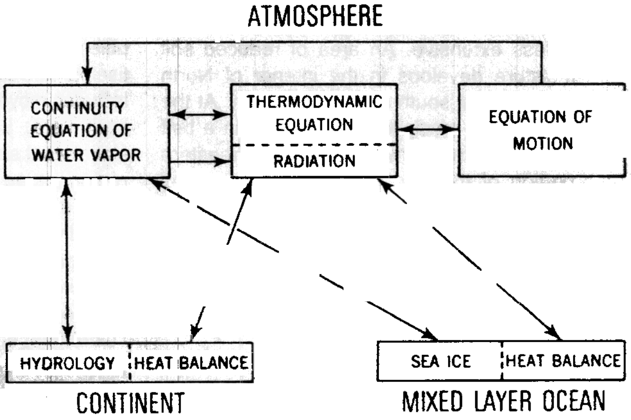

FIGURE 1. Box diagram illustrating the basic structure of the coupled atmosphere-mixed layer ocean climatic model.

Diagramme illustrant la structure de base que fait apparaître l'association des modèles atmosphériques et de la couche océanique mixte.

Over the continents, the assumption of no 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. Changes in soil moisture are computed from the rates of rainfall, evaporation, snowmelt, and runoff. 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. Further details of the hydrologic computations can be found in MANABE (1969).

TABLE I

Boundary conditions for control and ice sheet experiments

(P: present, L: last glacial maximum)

	Control	Ice Sheet
Land-Sea Distribution	P	L
Continental Ice Distribution	P	L
Atmospheric CO_2 Concentration (ppmv)	300	300
Snow-Free Land Albedo Distribution	P	P
Orbital Parameters	P	P

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 exchange 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.

EXPERIMENTAL DESIGN

To study the impact of continental ice on the LGM climate, two of the experiments run by BROCCOLI and MANABE (1987) are analyzed. One of these is a control experiment, using the modern distributions of land, continental ice, and surface albedo and the current atmospheric CO_2 concentration. The perturbed experiment uses the LGM distributions of land and continental ice, with all other factors held constant (Table I). The ice distribution is taken from the "maximum reconstruction" of HUGHES *et al.* (1981), and the land distribution

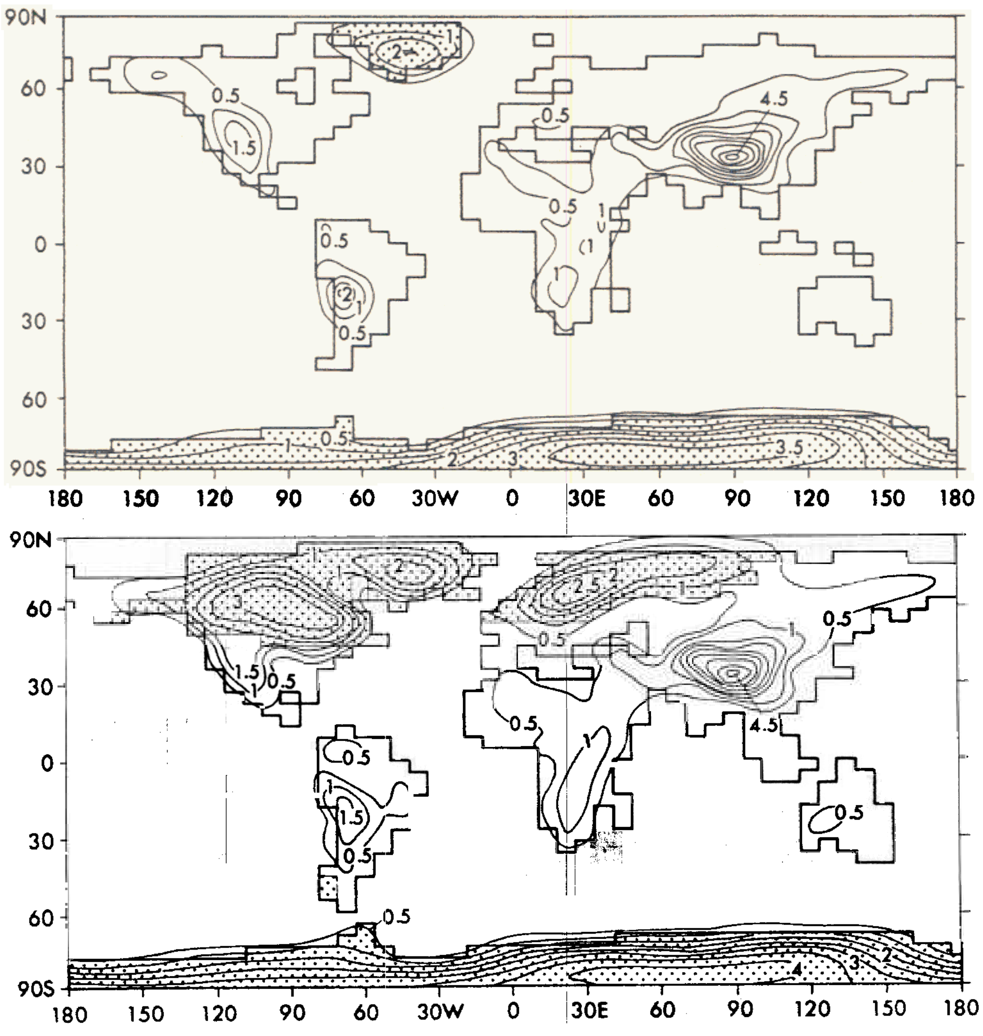

FIGURE 2. Continental outlines, topography, and distributions of continental ice used in models experiments. Topographic contours indicate height above sea level (km). Regions covered by continental ice are stippled. Top: present; bottom: last glacial maximum.

Profils des continents, topographie et répartition des glaciers continentaux qui ont servi aux essais de modélisation. Les courbes de niveau donnent l'altitude au-dessus du niveau de la mer (km). Les régions couvertes par les glaciers sont en pointillés. En haut: situation actuelle; en bas: dernier pléniglaciaire.

assumes a 150 m drop in sea level to accompany the increase in continental ice. The present and LGM coastlines and distributions of continental ice and topography used for these experiments are pictured in Figure 2.

Both versions of the model are time-integrated beginning from a dry, isothermal atmosphere at rest coupled to an isothermal ocean. A number of simulated annual cycles are required to "spin-up" the model before a quasi-equilibrium climate is achieved. The control and ice sheet experiments were integrated for 15 and 8 years, respectively, after the establishment of quasi-equilibrium conditions. It is from these periods that the model climates of the ice sheet and control experiments are taken and compared.

CLIMATIC RESPONSE

a) ATMOSPHERIC CIRCULATION

The presence of the massive ice sheet over the northern half of the North American continent, reaching elevations of more than 3000 m, has a major influence on the atmospheric circulation. Figures 3 and 4 contain winter (December-January-February) wind vectors for the surface and 515 mb level from the control and ice sheet experiments, respectively. At the 515 mb level, a dramatic change in the flow field between the two experiments is apparent. The almost zonal flow present in the control experiment, with only a weak ridge over western North America, is replaced by a pronounced blocking pattern in the ice sheet experiment. A split flow exists, with the stronger branch bypassing the Laurentide Ice Sheet to the south with a jet maximum just off the Atlantic coast, and a weaker branch following the northern periphery of the ice sheet to rejoin the southern branch over the North Atlantic. A distinct change in the flow pattern is also noted at the surface, where the mid-latitude westerly wind belt crossing the North Pacific is deflected northward over the Alaska-Yukon region. There it becomes part of an anticyclonic circulation centered over the western portion of the Laurentide Ice Sheet, with a strong surface flow crossing the northern periphery of the ice sheet before flowing across the North Atlantic. Over the remainder of North America, north to northwest flow originating from this anticyclone replaces the generally westerly flow of the control experiment. A similar, although weaker, flow pattern prevails during spring and autumn. In summer, the circulation in both experiments is much

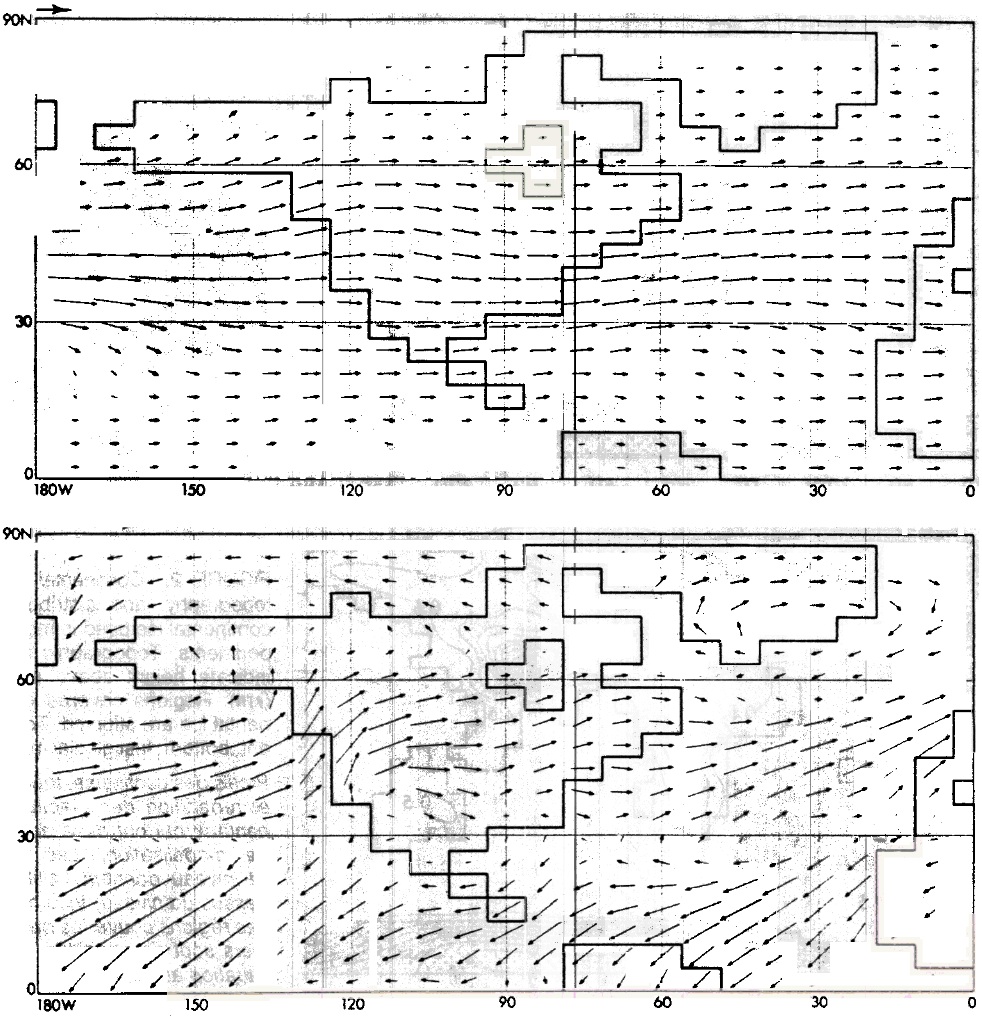

FIGURE 3. Wind vectors for winter from the control experiment. Magnitudes are proportional to the length of the vector and the arrow above the upper left corner of each map indicates a wind speed of 20m/s. Top: 515 mb level; bottom: surface.

Vecteurs vents selon l'essai témoin. L'importance des vents est proportionnelle à la longueur du vecteur et la flèche au-dessus de la partie supérieure du coin gauche de chacune des deux cartes donne une vitesse des vents de 20m/s. En haut: niveau de 515 mb; en bas: surface.

less vigorous, and only minor alterations of the flow occur. Some of the impacts of these changes in circulation on surface air temperature will be discussed in the next subsection.

b) TEMPERATURE

Pronounced cooling is associated with the expanded LGM continental ice in the North American sector. Figure 5 illustrates the change in surface air temperature for each season. Most prominent in all seasons is the sizeable cooling that is centered on the Laurentide Ice Sheet, reaching as much as 26° in winter. Two factors are important in producing this local cooling. One is the high surface albedo of glacial ice, which reduces the amount of solar radiation absorbed at the surface. In addition, points on the ice surface are at a much higher elevation than the corresponding points in the control experiment. Thus the decrease of temperature with height results in an additional reduction of surface air temperature.

Other regions of large temperature change are present outside the area covered by continental ice. Substantial cooling occurs over North America south of the ice front during winter, when temperatures drop by more than 6° over an area extending as far south as the Gulf of Mexico. The cooling in this region is less extensive in other seasons, particularly spring and summer, when higher temperatures occur in southeastern North America. Both changes in surface characteristics and airflow contribute to this seasonal contrast. In spring and summer, solar radiation is strong and the surface flow over the Gulf of Mexico region is from the south. There is more land in this region in the ice sheet experiment than in the control because sea level is lower. By substituting a continental surface with limited moisture content for a water surface, a greater burden falls upon the sensible heat flux as a mechanism for ventilating the surface. The increased sensible heating creates a local increase in temperature, which is advected northward by the surface flow. In autumn solar radiation begins to weaken, making this process less important, and the surface flow near the ice edge becomes northerly by winter, advecting air southward that has been cooled over the Laurentide Ice Sheet. In addition, more extensive winter snow cover in the ice sheet experiment also contributes to cooling during that season.

Elsewhere, a cooling maximum exists just offshore of the continent in the Labrador Sea region during winter and spring. MANABE and BROCCOLI (1985a) have described the mech-

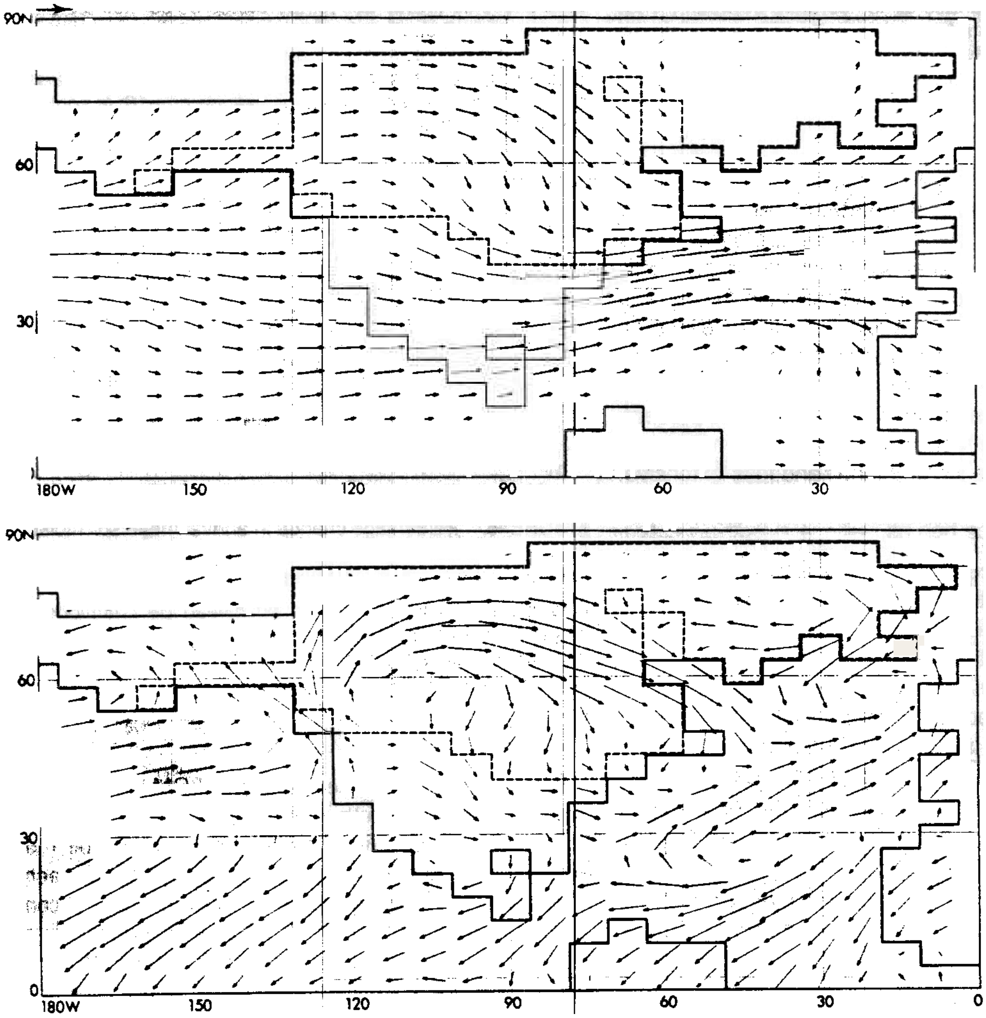

FIGURE 4. Same as Figure 3 except from the ice sheet experiment. The dashed outline indicates the continental ice boundary.

Même phénomène que sur la figure 3, mais cette fois selon l'essai sur le modèle d'inlandsis. Le tireté montre les limites des glaciers continentaux.

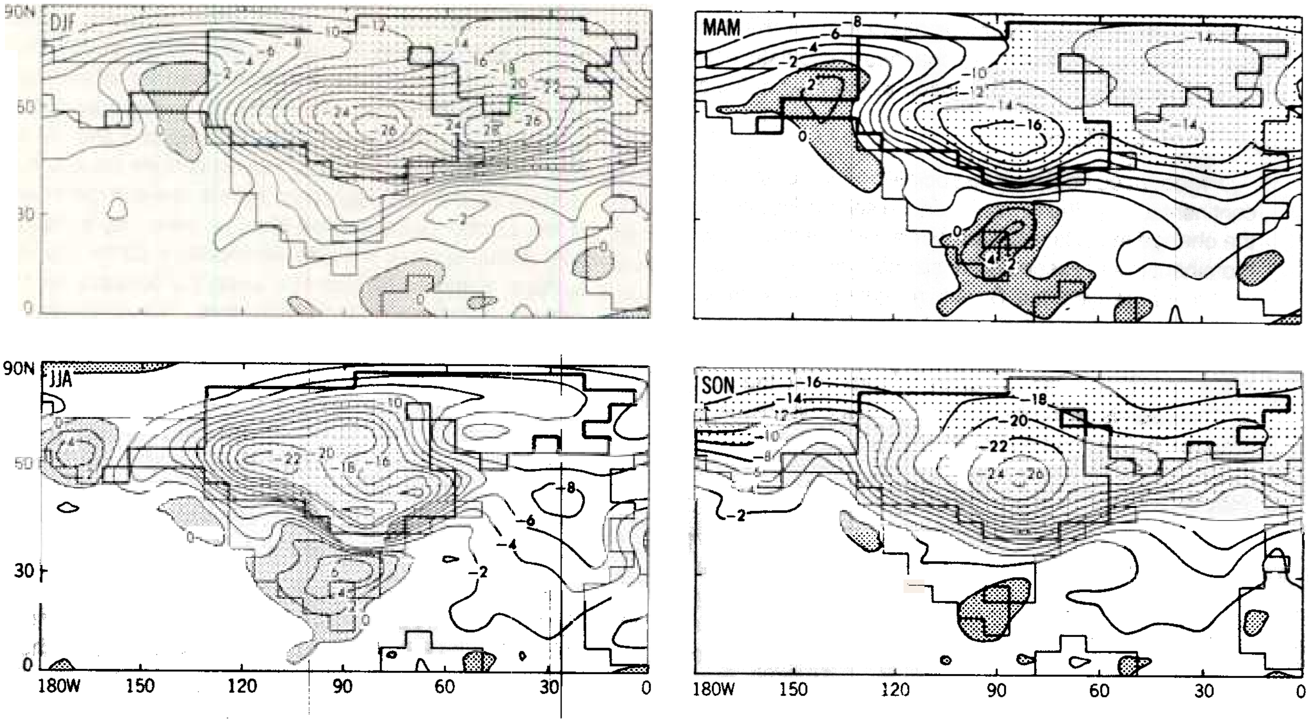

FIGURE 5. Difference in surface air temperature between the ice sheet and control experiments for each season (°C). Areas of temperature increase are densely stippled, while areas of temperature decrease greater than 10° are lightly stippled. The heavy solid outline indicates the continental ice boundary.

Différences au niveau des températures de surface à chacune des saisons entre l'essai sur le modèle d'inlandsis et l'essai témoin. Les régions qui connaissent une augmentation des températures sont densément pointillés, tandis que les régions qui connaissent une diminution des températures plus grande que 10° le sont moins. Le trait gras montre les limites des glaciers continentaux.

anism responsible for the large cooling in this location. Extremely cold air develops over the northern periphery of the Laurentide Ice Sheet and flows through the gap between the Laurentide and Greenland ice sheets to reach the North Atlantic Ocean. The effect of this cold air is to maintain thicker and more extensive sea ice in this region. The sea ice has an insulating effect and inhibits the heat exchange between the ocean and the overlying air, allowing much lower temperatures than in the control experiment where less sea ice is present. This mechanism is not effective in summer when the flow pattern is weaker and sea ice is thinner and less extensive, while in autumn it operates in a less dramatic fashion as the seasonal growth of sea ice begins.

Significant warming occurs in the model over the Alaska-Yukon region during winter and spring. Examination of the surface wind vectors indicates increased southerly flow in this region in response to the blocking effect of the Laurentide Ice Sheet. While no warming occurs in this region in autumn, a relative minimum of cooling extends northward from the Gulf of Alaska along the same axis. In summer, when the blocking pattern is not present, a relative maximum of cooling extends westward through this region from the ice sheet.

c) HYDROLOGY

The impact of the Laurentide Ice Sheet is not confined to atmospheric circulation and temperature, but also extends to the hydrologic budget of the model. Figure 6 is a map of the percentage change in annual mean soil moisture occurring in response to the presence of the LGM ice. A large area over the interior of North America south of the Laurentide Ice Sheet undergoes a substantial reduction of soil moisture, exceeding 60 % at its center. To investigate the mechanism responsible for this dry zone, a soil moisture budget is computed for each experiment. Figure 7 contains the seasonal variation of monthly mean soil moisture for this region from the ice sheet and control experiments, along with the difference in

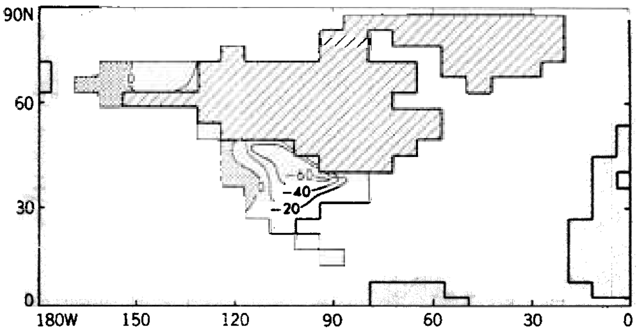

FIGURE 6. Percentage change in annual mean soil moisture from the control to the ice sheet experiment. Areas covered by continental ice are hatched; areas of positive soil moisture change are stippled.

Changements en pourcentage au niveau de l'humidité annuelle moyenne du sol selon l'essai témoin et l'essai sur le modèle d'inlandsis. Les régions couvertes par les glaciers continentaux sont hachurées et les régions dont le taux d'humidité augmente sont en pointillés.

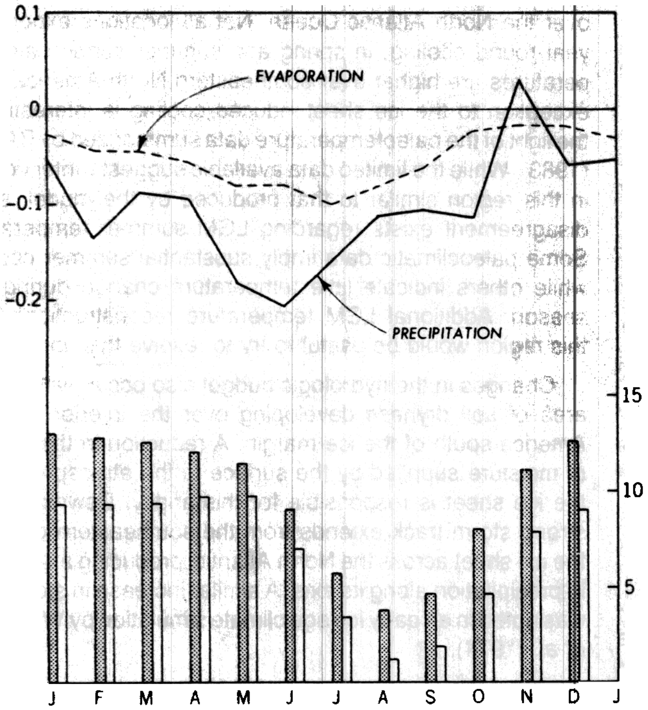

FIGURE 7. Seasonal variations in area-averaged soil moisture (cm) for the dry zone that develops south of the Laurentide Ice Sheet from the ice sheet and control experiments. The vertical bars indicate the monthly mean soil moisture, with the stippled and open bars representing the control and ice sheet experiments, respectively. Differences in precipitation and evaporation (including sublimation) between the two experiments (cm/d) are shown by solid and dashed lines, respectively.

Variations saisonnières de l'humidité moyenne du sol (cm) dans la région sèche qui se développe au sud de la calotte glaciaire laurentidienne selon l'essai sur le modèle d'inlandsis et l'essai témoin. Les colonnes donnent l'humidité mensuelle moyenne, la partie en pointillé représentant l'essai témoin. Les différences au niveau des précipitations et de l'évaporation (y compris la sublimation) entre les deux essais (cm/d) sont indiquées respectivement par un trait continu et par un tireté.

monthly mean precipitation and evaporation between the two experiments.

The budget shows that the reduction in precipitation in the ice sheet experiment is larger than the reduction in evaporation for nearly all months of the year. The smallest soil moisture differences occur in April and May, as the spring snowmelt common to both experiments replenishes the soil moisture. During the summer the soil dries in both experiments, but the drying is stronger in the ice sheet experiment because the ice sheet-induced reduction of precipitation is greater than the reduction of evaporation. The differences in soil moisture are then maintained through the autumn into winter, when the moisture storage in snow-covered soil changes little with time.

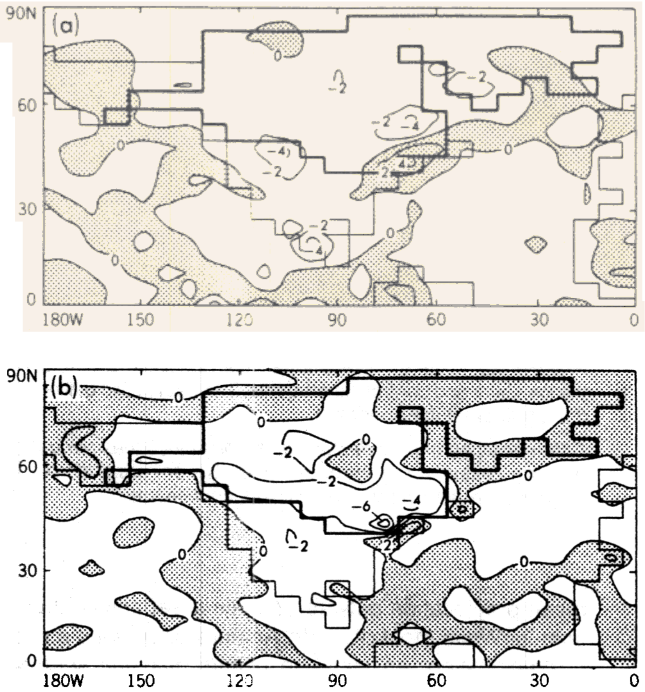

FIGURE 8. Differences in precipitation (top) and evaporation including sublimation (bottom) between the ice sheet and control experiments for the summer season. The heavy solid outline indicates the continental ice boundary. Units are mm/d.

Différences pour l'été au niveau des précipitations (en haut) et de l'évaporation, y compris la sublimation (en bas) entre l'essai sur le modèle d'inlandsis et l'essai témoin. Le trait gras donne les limites des glaciers continentaux. Les unités sont en mm/d.

This analysis suggests that the large decrease in summer precipitation produces a significant depletion of soil moisture over interior North America. To understand its origin, Figure 8 is constructed showing the differences in the rates of precipitation and evaporation (including sublimation) between the two experiments during summer. This figure indicates that a decrease in precipitation rate occurs over the dry region of interior North America. locally reaching as much as 4 mm/d just south of the ice sheet. Although most Northern Hemisphere continental regions experience a reduction in precipitation, the decrease in this area is much larger than average. While a reduction in evaporation rate also occurs in this region, it is smaller in magnitude. In contrast, a large decrease in evaporation and sublimation occurs over the Laurentide Ice Sheet, particularly at its southern margin, reducing the amount of moisture available to the atmosphere, as the cold ice sheets are a poorer moisture source than the warmer soil of the control experiment. This suggests that the decrease in the amount of moisture supplied to the atmosphere from the Laurentide Ice Sheet contributes to the increased aridity of the region to its south. The ice sheet acts as a moisture sink, drawing atmospheric water vapor away from nearby areas and reducing its availability for precipitation. The interior of North America is sensitive to this effect since it is relatively isolated from oceanic moisture sources and regions of maritime cyclogenesis. MANABE and BROCCOLI (1985a) discuss this mechanism in more detail.

Not all locations in the North American sector experience decreased precipitation in the ice sheet experiment. Figure 9 is the geographical distribution of the change in annual

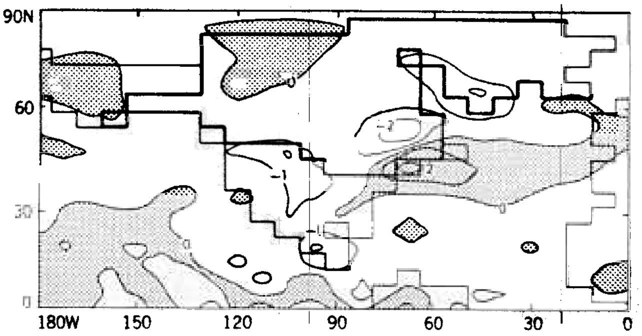

FIGURE 9. Differences in annual mean precipitation (mm/d) between the ice sheet and control experiments. The heavy solid outline indicates the continental ice boundary.

Différences au niveau des précipitations moyennes annuelles (mm/d) entre l'essai sur le modèle d'inlandsis et l'essai témoin. Le trait gras montre les limites des glaciers continentaux.

mean precipitation between the ice sheet and control experiments. While most of North America undergoes a decrease in precipitation, an increase occurs near the southeastern corner of the Laurentide Ice Sheet. This area is part of a band of increased precipitation extending eastward across the North Atlantic. BROCCOLI and MANABE (1987) associated a similar belt of increased precipitation (in an experiment incorporating all LGM boundary conditions) with a strengthening of the westerlies and increased storminess extending from the southeastern corner of the Laurentide Ice Sheet across the North Atlantic and skirting the southern edge of the Scandinavian Ice Sheet. They also speculated that increased snowfall over these regions may be important to the snow budgets of both ice sheets, raising the possibility that an ice sheet-induced storm track may form part of a self-sustaining mechanism for ice sheet growth and maintenance.

CONCLUDING REMARKS

In response to the incorporation of the expanded continental ice sheets of the LGM, a climate model consisting of an atmospheric general circulation model coupled with a simple model of the oceanic mixed layer produces major changes in the climate of North America. During all seasons but summer, blocking associated with the Laurentide Ice Sheet results in a split flow in the middle troposphere straddling the ice sheet. At the surface, the midlatitude westerlies are deflected northward along the west coast of the continent, and an anticyclonic circulation is formed over the western portion of the ice sheet. North to northwest surface flow replaces the generally westerly flow of the control experiment over the remainder of North America. KUTZBACH and GUETTER (1986) found a similar modification of the tropospheric flow in their simulation of the climate at 18 ka.

Pronounced cooling occurs in the North American sector in response to these circulation changes and to the reflection of solar radiation by the high-albedo ice sheet. This reduction in temperature is most extensive in winter, when the strong cooling extends southward to the Gulf of Mexico and eastward over the North Atlantic Ocean. Not all locations experience year-round cooling; in spring and summer surface air temperatures are higher over southeastern North America. This exception to the ice sheet-induced cooling is interesting in the light of the paleotemperature data summarized by BARRY (1983). While the limited data available suggest winter cooling in this region similar to that produced by the model, some disagreement exists regarding LGM summer temperature. Some paleoclimatic data imply substantial summer cooling, while others indicate little temperature change during that season. Additional LGM temperature reconstructions from this region would be useful to try to resolve this uncertainty.

Changes in the hydrologic budget also occur, with a large area of soil dryness developing over the interior of North America south of the ice margin. A reduction in the amount of moisture supplied by the surface to the atmosphere over the ice sheet is responsible for this aridity. Downstream, a strong storm track extends from the southeastern corner of the ice sheet across the North Atlantic, producing an increase in precipitation along its axis. A similar increase in storminess was noted in an early ice age climate simulation by WILLIAMS *et al.* (1974).

Many of these results are interesting because of their similarity to paleoclimatic inferences based on geological data. WELLS (1983) reconstructed the Late Pleistocene surface airflow over central North America from eolian landforms. He found the direction of late glacial surface winds to be from 40 to 90 degrees out of phase from the present-day circulation. East of the Rockies, a northwesterly surface flow prevailed during the Late Wisconsinan, while a south to southwest flow was prevalent in western North America. The flow field produced in the ice sheet experiment during winter (when winds are strongest) is very similar to that reconstructed by Wells. In addition, the reduction of central North American soil moisture in the model is consistent with the arid conditions required for the extensive dune formation that occurred in the Great Plains during the Late Wisconsinan. While the dating as reported by Wells does not allow the identification of a narrow time interval for dune formation, it suggests that the dunes were formed during the latter stages of and just after the LGM.

The presence of loess in the Great Plains and Mississippi Valley region (*e.g.*, SCHEIDIG, 1934) is also of interest, since it is often assumed that a dry climate (or, at least, a climate with a pronounced dry season) is necessary for the transportation and deposition of loess material by the wind. If the glacial origin and eolian deposition of loess are accepted (SMALLEY, 1972; KUKLA, 1975), then these loess deposits suggest that such a climate existed near the time of the last glacial maximum. The region of increased aridity in interior North America in the ice sheet experiment is consistent with these inferences.

The paleoclimatic data described above suggest that some of the changes in climate simulated by the atmosphere-mixed layer ocean model in response to the LGM distribution of continental ice are consistent with those implied by geological data. This adds confidence to other climatic effects produced by the model in the ice sheet experiment. The model used in this study represents the state of the art, but it can only approximate the response of the actual climate system. Future studies of a similar nature using higher resolution or more complete climate models (*e.g.*, models including an interactive dynamic ocean) are necessary to further our understanding of the ice age climate. Continued efforts in collecting and synthesizing paleoclimatic data are valuable in providing climate modelers with tools for evaluating their results.

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