CLIMATE MODEL STUDIES OF INTERACTIONS BETWEEN ICE SHEETS AND THE ATMOSPHERE-OCEAN SYSTEM

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ABSTRACT

A number of climate modeling studies have been conducted at the Geophysical Fluid Dynamics Laboratory to study the interaction of continental ice sheets with the climate system. This paper reviews some of the primary results from these studies. Substantial changes in atmospheric circulation, location and intensity of storm tracks, precipitation distribution, sea surface temperature, sea ice extent, and soil moisture occur in response to the ice sheets of the last glacial maximum. Estimates of the mass budgets of these ice sheets suggest that they are not in equilibrium with the simulated LGM climate, although questions regarding the refreezing of surface meltwater make this result uncertain. Results from climate model experiments with and without orography suggest that orographic uplift could have produced a climate slightly more favorable for ice sheet initiation.

1. INTRODUCTION

Since the cycles of Pleistocene glaciations were recognized during the nineteenth century, scientists have used the waxing and waning of continental ice sheets as indicators of long term variations in the earth's climate. When regarded in such fashion, the ice sheets can be viewed as responding to some type of climate forcing, such as that provided by variations in orbital parameters. However by virtue of their vastness, one can reasonably expect continental ice sheets to exert a substantial influence on local, regional, and even global climate. Thus ice sheets are an important component of the climate system, both responding to external forcing and inducing other responses within the atmosphere-ocean system. An improved understanding of these mutual interactions may be essential to a better understanding of past and future variations in climate.

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In this paper we will review some climate modeling experiments conducted at the Geophysical Fluid Dynamics Laboratory that are relevant to the role of ice in the climate system. On geological time scales these can be regarded as "snapshot" experiments in which continental ice extent, orbital parameters, and atmospheric composition corresponding to a particular time period are prescribed as boundary conditions. The simulated climate represents a "snapshot" of climatic conditions that are in equilibrium with those boundary conditions. Thus the only time-dependence considered in these experiments involves those parts of the climate system that respond relatively quickly (i. e., atmosphere, land surface, sea ice, ocean mixed layer). Time-dependent changes in continental ice extent, orbital parameters, and atmospheric composition have not been included. Despite this limitation, such experiments can be quite useful for identifying the physical mechanisms that are important in maintaining a particular climatic regime. They can also allow inferences to be drawn about the sensitivity of climate to changes in those parts of the atmosphere-ocean-cryosphere system that vary more slowly.

This paper will discuss a subset of the many ways in which ice can interact with the atmosphere-ocean system. In section 2 we discuss the direct influence of continental ice sheets on the atmosphere-ocean system. Substantial changes in the atmospheric flow field, location and intensity of storm tracks, precipitation distribution, sea surface temperature, sea ice extent, and soil moisture occur in response to the ice sheets of the last glacial maximum (LGM). Section 3 contains estimates of the simulated mass budgets of continental ice sheets and how they change in response to different forcing. Section 4 contains some speculation about the role of orography in creating an environment favorable for ice sheet initiation, and section 5 contains a brief discussion of subjects for future investigation.

2. EFFECTS OF ICE SHEETS ON ATMOSPHERE-OCEAN SYSTEM

A series of climate model experiments has been conducted at GFDL to explore the physical processes by which a glacial climate is maintained. Most of the results presented in this and the following section are discussed in more detail in the original papers (Manabe and Broccoli, 1984, 1985; Broccoli and Manabe, 1987a, 1987b). The model used for these studies was constructed by combining a general circulation model of the atmosphere with a simple mixed layer ocean model and a simple heat and water budget model of the land surface, and is very similar to that used to study greenhouse gas-induced changes in climate (Manabe and Stouffer, 1979, 1980). The earlier experiments (Manabe and Broccoli, 1984, 1985) examined the effects of ice sheets alone without any other changes in boundary conditions. As an extension of this work Broccoli and Manabe (1987a) performed four integrations, each with a different set of boundary conditions, to assess the contributions of expanded continental ice sheets, reduced atmospheric CO_2, and changes in snow-free land albedo to the maintenance of the LGM climate. Their experiments are described in Table 1. Most of the discussion in this section will focus on the simulated response of the climate to the LGM continental ice. This can be determined by comparing integrations E2 and E1 or the analogous pair of experiments in the earlier work of Manabe and Broccoli (1984, 1985).

Experiment	Continental ice and land/sea distribution	Atmospheric CO_2 concentration (ppm)	Snow-free land albedo
E1	Present	300	Present
E2	LGM	300	Present
E3	LGM	300	LGM
E4	LGM	200	LGM

Table Boundary conditions for climate model integrations of Broccoli and Manabe (1987a).

To provide some perspective on the contribution of the expanded ice sheets to the glacial climate, the response of surface air temperature to expanded continental ice can be compared with the total response to all LGM boundary conditions (Fig. 1). The extreme interhemispheric asymmetry of the ice sheet-induced response is evident, with the cooling largest in the high latitudes of the Northern Hemisphere and decreasing southward. A secondary maximum occurs poleward of 60° S due to the influence of an expanded Antarctic ice sheet. Continental ice provides a substantial majority (~60%) of the simulated reduction in surface air temperature in the Northern Hemisphere, while providing only a small fraction (~15%) of the Southern Hemisphere cooling (Broccoli and Manabe, 1987a).

2.1 Atmospheric Circulation

Substantial changes in the midtropospheric flow field occur in response to the LGM distribution of land ice, as evident from a comparison of the ice sheet and standard

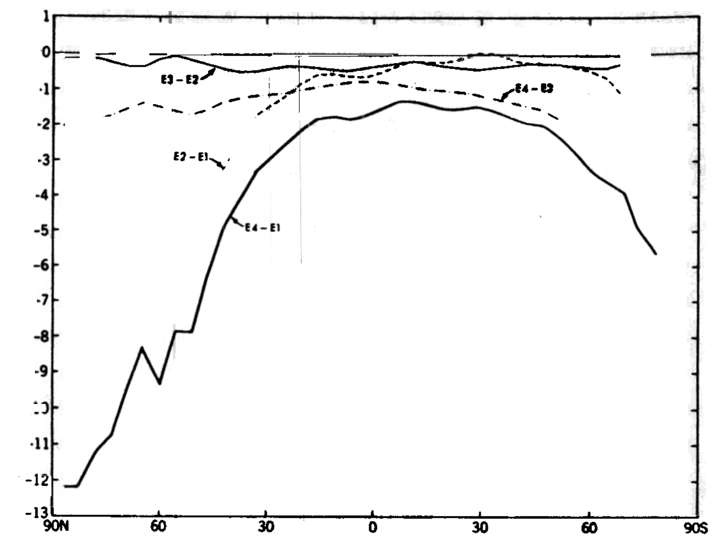

Fig. 1. Latitudinal distribution of annually averaged difference in zonal mean surface air temperature (deg K) between the following pairs of integrations: E2-E1 (ice sheet effect), E4-E3 (CO_2 effect), E3-E2 (albedo effect), and E4-E1 (combined effect). Only gridpoints free of continental ice in all four integrations are used in computing the differences.

experiments of Manabe and Broccoli (1984, 1985). The distribution of wind speed at 515 mb from the ice sheet experiment (Fig. 2) for boreal winter reveals a split flow structure straddling the Laurentide ice sheet. The northern wind maximum (the weaker of the two) curves anticyclonically across northwestern North America, while the southern branch becomes very intense just off the east coast of that continent. No such split flow structure exists in the standard experiment, where the single jet present is considerably weaker than the corresponding southern branch of the ice sheet jet. Thus the Laurentide ice sheet is responsible for creating a split flow and intensifying the midtropospheric wind maximum located downstream of North America.

At the surface, a strong anticyclone is present over northwestern North America in the ice sheet experiment. An intense surface flow originating from this anticyclone follows the northern periphery of the North American ice sheet and eventually passes between the Greenland and Laurentide ice domes to reach the Labrador Sea, paralleling the northern branch of the midtropospheric split flow. This is an ideal path for extremely cold air masses to follow and invade the North Atlantic Ocean. Thick sea ice is formed in this area, reducing the heat exchange between the sea water and the overlying air and inhibiting the warming of the air mass.

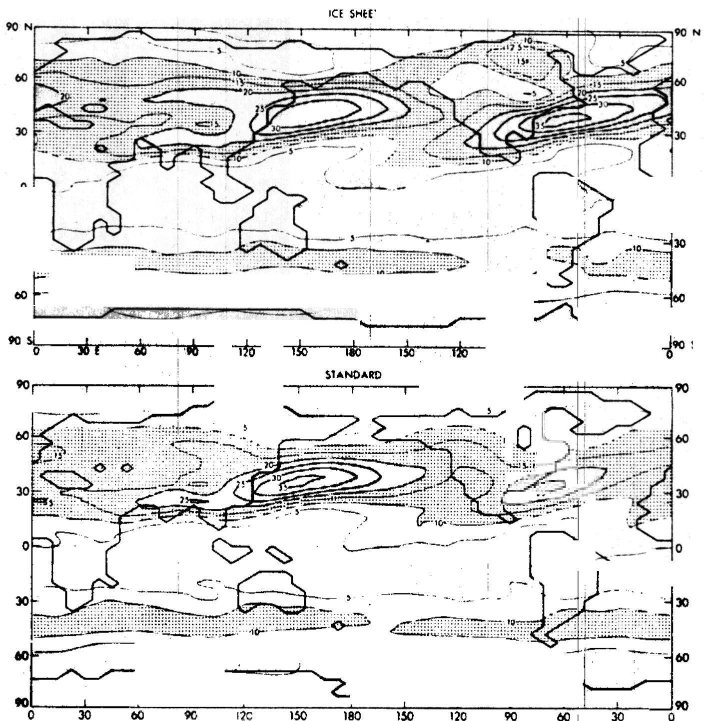

Fig. 2. Wind speeds for the DJF season at 515-mb level (m/s). Top: ice sheet integration. Bottom: standard integration.

2.2 Ocean Heat Budget

The sea surface temperature (SST) change that occurs in response to the LGM ice sheets shows an interhemispheric asymmetry similar to that of surface air temperature. While only small changes occur in the Southern Hemisphere, SSTs in the northern hemisphere are significantly colder in the ice sheet experiment (Fig. 3). In both February and August the ice sheet-induced SST difference is most pronounced in the midlatitudes of the North Atlantic and the North Pacific. The cooling over the Atlantic is generally larger than the corresponding cooling over the Pacific. These features are in qualitative agreement with the difference reconstructed by CLIMAP between the LGM and modern SST distributions.

The zones of maximum winter SST difference over the northern hemisphere oceans of the model approximately coincide with the winter sea ice margin from the ice sheet experiment. This close relationship between the sea ice margin and the SST difference is evident in Fig. 4, which includes the latitudinal profiles of zonal mean sea ice

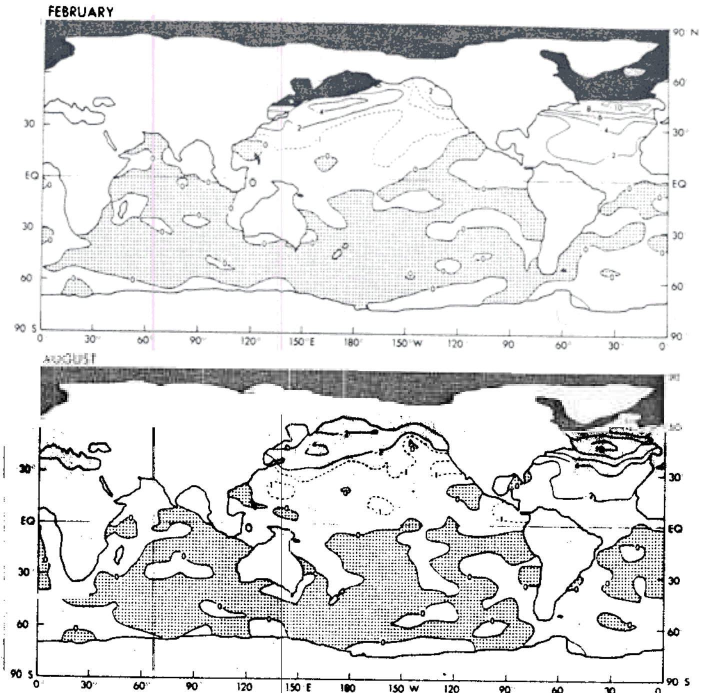

Fig. 3. Sea surface temperature difference (deg K) between ice sheet and standard integrations. Stippling indicates positive difference. Top: February. Bottom: August.

thickness, SST, and surface air temperature for the North Atlantic Ocean during the winter season. Since the temperature of water below sea ice cannot fall below freezing (i. e., ~271.2 K), the meridional gradient of mixed layer temperature is zero poleward of the sea ice margin and negative equatorward of that margin. Thus the difference in the zonal mean SST is a maximum near the sea ice margin of the ice sheet experiment and becomes zero poleward of the sea ice margin of the standard experiment.

The changes in surface air temperature are also related to the sea ice margin. In both the ice sheet and standard experiments the zonal mean air-sea temperature difference increases sharply from the margin of sea ice toward higher latitudes, where sea ice is thicker and heat exchange between the ocean and the overlying air is reduced. Since the sea ice margin in the ice sheet experiment is located to the south of the sea ice margin in the standard experiment, there is a zonal belt between 47°N and 60°N where sea ice exists only in the ice sheet experiment. In this belt the air-sea temperature difference in the ice sheet experiment is much larger than in the standard

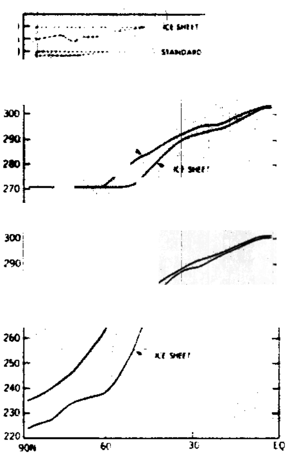

Fig. 4. Latitudinal distributions of zonally averaged atmospheric and oceanic parameters for the North Atlantic Ocean during winter from the ice sheet and standard integrations. Top: sea ice thickness (m). Center: Sea surface temperature (deg K). Bottom: surface air temperature (deg K).

experiment because of the insulating effect of sea ice. The result is the large ice sheet-induced difference in surface air temperature located just to the north of the winter sea ice margin from the ice sheet experiment.

2.3 Storm Tracks and Precipitation

The aforementioned ice sheet-induced changes in the atmospheric flow are associated with changes in storm tracks and associated precipitation. As discussed previously, the midlatitude westerlies are strengthened substantially from eastern North America across the North Atlantic and into southern Europe and central Asia. A belt of reduced sea level pressure parallels this region of enhanced westerlies. Increased storminess is also found along the axis of this belt, associated with a cyclone track which extends from the east coast of North America just south of the ice sheet to the western margin of the Eurasian ice sheet.

This enhanced storm track may have interesting implications for the growth and maintenance of the northern hemisphere ice sheets. Cyclones developing in its western portion induce heavy precipitation near the southeastern portion of the North American ice sheet, causing an increase in precipitation rate in this region, as depicted in Fig. 5. This precipitation, which falls primarily in the form of snow, is important to the snow budget of this ice sheet. The increase in precipitation associated with this storm track also extends eastward into the European sector, where it represents a source of snow for the Eurasian ice sheet. The close association between this band of storminess and increased precipitation and the southern margins of the North American and Eurasian ice sheets raises a possibility of a self-sustaining, or positive feedback mechanism for ice sheet growth and maintenance. In addition, it is conceivable that the existence of continental ice over North America may contribute to a more favorable environment for the southward extension of ice in Europe. Additional experiments would be required, however, to evaluate the potential importance of these mechanisms to ice sheet growth and maintenance.

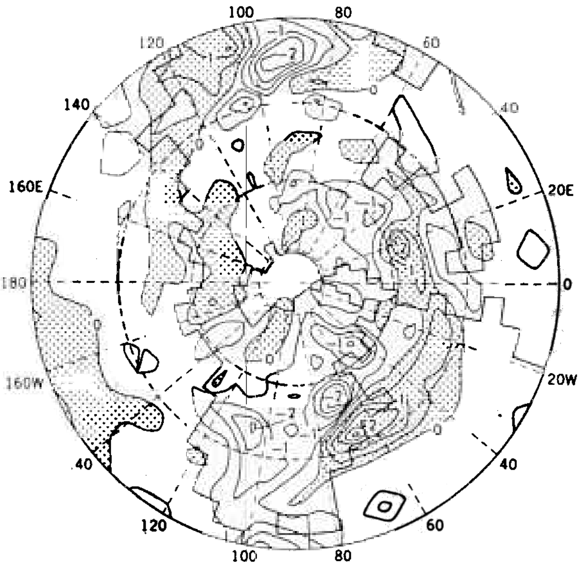

Fig. 5. Difference in annual mean precipitation (mm/d) between experiments E2 and E1 of Broccoli and Manabe (1987a). Regions of increased precipitation are stippled.

2.4 Soil Moisture

Ice sheet-induced changes in soil moisture are of interest since they can provide some insights into changes in the spatial distribution of vegetation between glacial and interglacial periods. In addition, soil moisture changes can be inferred from botanical and geological evidence of past glacial climates, allowing a comparison with model results. Areas of substantially reduced soil moisture occur in the ice sheet experiment (Fig. 6). Of particular interest are two regions: one extending from eastern

Europe across much of north central Asia and lying just south of the Eurasian ice sheet, and another, less extensive area which adjoins the southern margin of the North American ice sheet in a similar manner. Both regions experience statistically significant reductions in soil moisture (according to a simple t-test) and their proximity to the major ice sheets makes them interesting places to examine the effects of continental ice sheets on the hydrologic budget.

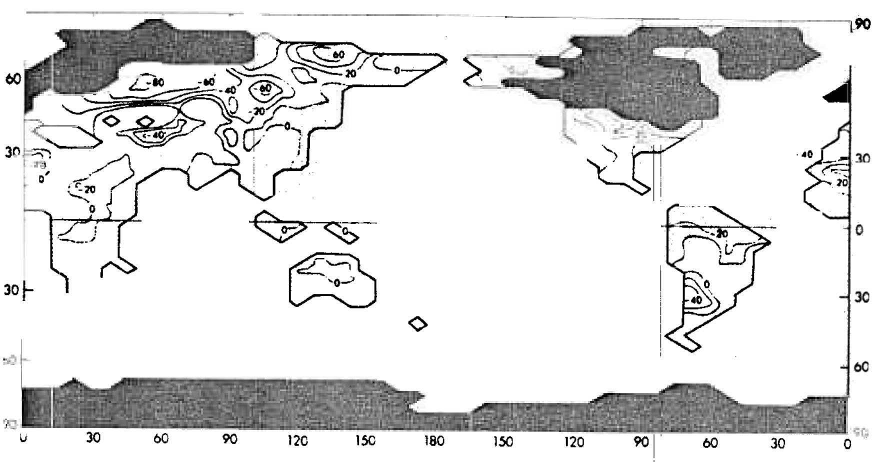

Fig. 6. Percentage change in annual mean soil moisture from the standard to the ice sheet integration. Areas covered by continental ice are blacked out; stippling indicates areas with an increase of soil moisture. No contours are drawn in areas of soil moisture increase.

An examination of the seasonal march of soil moisture for both of these regions indicates that it is smaller in the ice sheet experiment for nearly all months of the year. The difference is smallest in June, as spring snowmelt has replenished the soil moisture in both experiments. The difference in soil moisture grows during summer as the ice sheet-induced reduction in precipitation is larger than the corresponding reduction in evaporation. The soil moisture differences, having thus developed during summer, are maintained during the late autumn and winter seasons when the moisture storage in the snow-covered soil changes very little.

Maps of the ice sheet-induced differences of summer precipitation and evaporation (including sublimation) suggest a mechanism responsible for this dryness (Fig. 7). A major decrease in evaporation and sublimation occurs over both the North American and Eurasian ice sheets, particularly at their southern margins. This constitutes a reduction in the supply of moisture to the atmosphere relative to the standard experiment, where warmer soil is a more abundant moisture source than the cold ice sheets. From this evidence we hypothesize that the ice sheets are, relatively speaking, moisture sinks that draw atmospheric water vapor away from surrounding regions and reduce its availability for precipitation, particularly in summer. The regions adjacent to the southern margins of the ice sheets are especially sensitive to this effect because they are relatively isolated from oceanic moisture sources and because the reduction of evaporation is largest near the ice sheet margins.

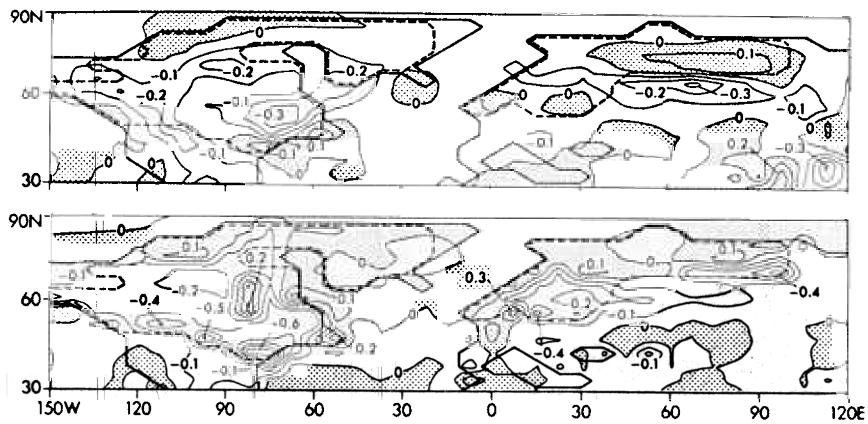

Fig. 7. Difference in precipitation (top) and evaporation including sublimation (bottom) between the ice sheet and standard integrations for the summer season. Units are cm/d. The dashed lines indicate the boundaries of continental ice in the ice sheet integration.

3. ICE SHEET MASS BUDGET

Although the ice sheet topography is kept fixed throughout the course of the numerical experiments described in this paper, it is possible to analyze the various components of the mass budget at the ice surface. The mass budget of a continental ice sheet can be determined by area-averaging the positive contribution due to accumulation and the negative contribution due to ablation. Since the climate model does not account for ice sheet dynamics, the negative contribution due to calving at the ice sheet margin cannot be estimated. Thus the accumulation is taken to be equal to the snowfall, while the ablation processes considered are sublimation from the ice surface and surface melt. In this ice budget analysis it is assumed that all meltwater runs off without refreezing.

Table 2 contains area-averaged annual mean values of snowfall, sublimation, and surface melt for the North American and Eurasian ice sheets from the experiment of Manabe and Broccoli (1985). It is evident that the negative contribution from surface melt and sublimation far exceeds the positive contribution from snowfall, implying a net depletion of ice for both ice sheets. Of the two ablation processes the surface melt is larger than the ablation by a factor of five, being by far the most important term in the budget.

	North American	Eurasian
Snowfall	0.158	0.138
Sublimation	0.068	0.061
Surface melt	0.302	0.365
Net	-0.211	-0.288

Table 2: Annual mean area-averaged ice budget components (cm/d) for the North American and Eurasian ice sheets from the ice sheet experiment of Manabe and Broccoli (1985).

The seasonal variation for the ice budget averaged over the entire North American ice sheet is illustrated in Fig. 8. The area-averaged snowfall rate varies little with season, while the sublimation undergoes a modest seasonal variation with a winter maximum. In contrast the area-averaged surface melt experiences an extremely large seasonal variation. Little or no surface melt occurs from November through March, but very large values occur during the warm season.

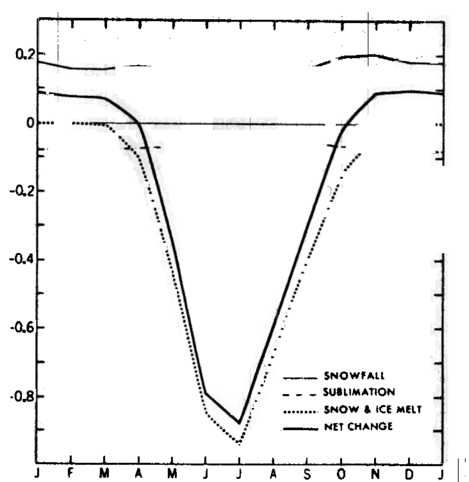

Fig. 8. Seasonal variation of area-averaged ice budget components for the North American ice sheet from the ice sheet integration (cm/d).

An examination of the spatial distribution of the annually averaged ice budget (Fig. 9) indicates that an extremely rapid depletion of ice occurs in a relatively narrow belt along the southern margin of both ice sheets. A slow accretion takes place over most of the remaining portions. The processes responsible for the rapid surface melt become evident when one examines the latitudinal distributions of various heat budget components at the surface of the North American ice sheet (Fig. 10). Near its southern margin, where the most rapid surface melt occurs, the ice sheet gains heat through a large downward flux of sensible heat. This is mainly due to the development of intense temperature inversions near the cold surface of the ice sheet during the warm season. It is of interest to note that the ice sheet also gains heat in this region during summer through the downward flux of latent heat (i.e., the condensation of water vapor). This suggests that the air is relatively humid near the ice surface.

The results from these ice budget calculations suggest that both ice sheets would ablate very rapidly in the model climate produced in the ice sheet experiment. While this experiment does not consider other changes in boundary conditions representative of the LGM (such as reduced atmospheric CO_2 and changes in the albedo of snow- and ice-free surfaces), the effects of these additional changes can be determined by an examination of the ice budgets in the experiments of Broccoli and Manabe (1987a). Results from their experiments indicate that the simulated ice budgets are also negative when all LGM boundary conditions are included in the model, although the rate of depletion of the ice is smaller by approximately 15-20%. Compared the ice sheet experiment (E2), the effect of incorporating the remaining changes in boundary conditions is to decrease the surface melt by an amount that more than compensates for a small reduction in snowfall.

There are difficulties in interpreting these results due to the simplified representation of the ice sheets in the climate model. The combination of the relatively coarse resolution of the model and the spherical harmonic representation of the ice sheet topography may not adequately represent the geometry of the ice sheet surface. Since the local mass balance of an ice sheet is highly dependent on the surface elevation, this may lead to errors in the estimation of the mass balance.

A more important difficulty concerns the fate of the water produced by surface melting. When surface melt occurs at the surface of an ice sheet, some of the meltwater percolates down into deeper layers of ice, where temperatures could be well below freezing. Thus while the ice sheet would gain heat, mass would not be lost from the system (Paterson, 1981, pp. 7-8). In the climate model (as diagnosed from a heat balance calculation), all meltwater is assumed to run off and be permanently lost to the system. This suggests that the melt rates we have computed represent an upper limit to the actual loss of ice due to surface melting. In the absence of a technique that can

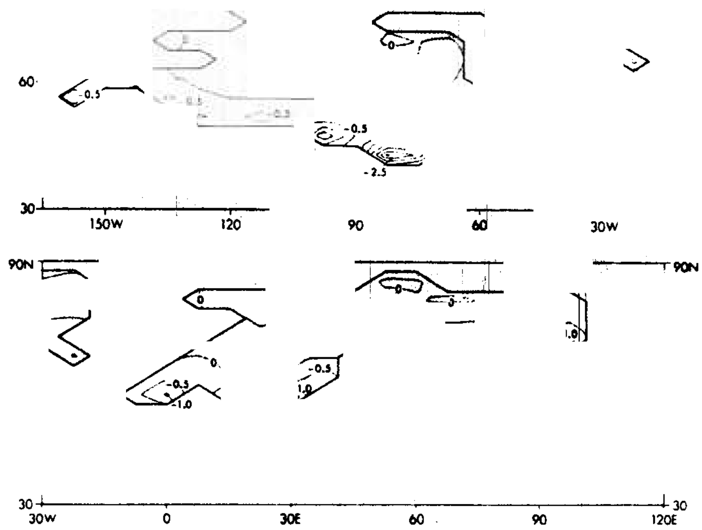

Fig. 9. Geographical distribution of the annually averaged mass balance (cm/d) from the ice sheet integration. Regions of net ice accretion are shaded. Top: North American ice sheet. Bottom: Eurasian ice sheet.

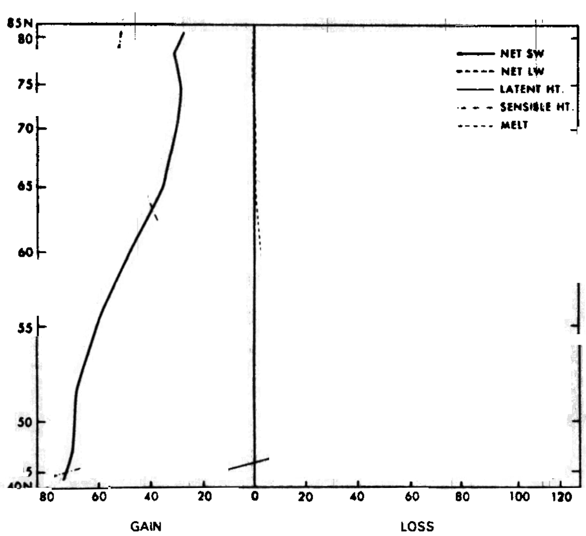

Fig. 10. Latitudinal distribution of annually averaged zonal mean surface heat budget components (W/m^2) for the North American ice sheet from the ice sheet experiment. The latitude scale is adjusted to reflect the ice sheet area in each latitude belt.

be applied to climate model output to determine the fate of surface meltwater, the question of whether or not the LGM ice sheets are in equilibrium with the simulated climate cannot be answered from mass balance calculations of this kind.

4. ICE SHEET INITIATION

Ruddiman and his collaborators have suggested that recent changes in the earth's orography may have contributed to many of the changes in climate that have occurred from the late Tertiary into the Quaternary (Ruddiman et al., 1986; Ruddiman and Raymo, 1988; Raymo and Ruddiman, 1992). Evidence has been assembled to suggest that much of the uplift of the Tibetan Plateau and the western United States may have occurred in the last 10 million years, as documented in Ruddiman et al. (1989). A hypothesis that received particular emphasis in their early work is that these changes in orography have induced changes in atmospheric circulation that create a more favorable environment for the initiation of Northern Hemisphere ice sheets. Such changes involve the establishment or enhancement of longwave troughs over eastern North America and western Europe that would cool these regions (due to increased northerly winds) and provide precipitation for the nourishment of ice sheets (due to storm tracks immediately downstream of the trough axes). Climate modeling experiments have been conducted to explore the role that orographic uplift may have played in these and other aspects of late Cenozoic climate change (Ruddiman and Kutzbach, 1989; Kutzbach et al., 1989).

A climate sensitivity experiment that was performed to investigate the role of orography in the maintenance of midlatitude arid climates (Manabe and Broccoli, 1990; Broccoli and Manabe, 1992) allows a further exploration of the possible role of orographic uplift in setting the stage for the periodic glaciations of the Pleistocene. Two integrations were conducted with the GFDL climate model. In one of these integrations realistic geography and orography were used. In the other, the same geographical distribution of land and sea was used, but with flat continents. These integrations will subsequently be identified as the mountain (M) and no-mountain (NM) integrations, respectively. While the changes in orography that are likely to have occurred during the last 10 million years are less dramatic than the extremes represented by these integrations, the design of this experiment does allow inferences to be drawn about the response of climate to such changes.

As discussed by Broccoli and Manabe (1992), the presence of orography in the M integration results in the alteration of the atmospheric circulation from a relatively zonal pattern to one that features stationary waves and enhanced meridional flow.

Increased northerly flow in the lower troposphere in the Hudson Bay region occurs in the M experiment, as the axis of a longwave trough is located over eastern North America. Accordingly, an area of enhanced southerly flow can be found downstream over the North Atlantic and the adjacent coast of eastern Canada. The positions of these features shift somewhat with season, tending to be farther east in autumn and winter than in spring and summer. Because most ablation occurs in the spring and summer seasons when insolation is strong, the changes in circulation and temperature during these seasons may be of most relevance to the establishment of ice sheets.

Large changes in surface air temperature during spring and summer occur in response to orography in a variety of locations (Fig. 11, top). The cooling evident over eastern Canada and Scandinavia is particularly interesting, since these regions were the sites of the Laurentide and Scandinavian ice sheets. Some caution is required in the interpretation of these results due to the idealized nature of the experimental design. Strictly speaking, the evidence for geologically recent uplift applies to the Tibetan Plateau and areas (such as the Colorado Plateau) in the western United States. However the difference between the M and NM integrations represents not only orographic changes in these regions, but everywhere else as well. Thus local changes in the height of the surface may account for some of the changes in temperature between the M and NM integrations.

To assess the importance of this effect, the surface air temperatures from the M experiment have been reduced to sea level by assuming a decrease of temperature with height of 6.5^{o}/km. While this is a very crude form of adjustment, it provides a way of separating the temperature changes of interest (i. e., due to altered circulation) from those that are a result of local changes in terrain height. The changes in adjusted surface air temperature during spring and summer (Fig. 11, bottom) show that most of the cooling over eastern Canada remains intact, with a magnitude of 1-3^{o}, but that the Scandinavian cooling is no longer present. The 830 mb vector wind difference between the M and NM integrations (Fig. 12) over eastern Canada is primarily from the north and east. This is due to the presence of a cyclonic vortex northeast of Hudson Bay in the M integration as opposed to a relatively uniform strong zonal flow in the NM experiment. Thus the region of cooling over eastern Canada is associated with a tendency for an increased maritime influence in the M integration during a season when lingering sea ice and cold surface waters prevent air temperatures from rising as rapidly as over the continental interior.

While these changes in temperature are relatively modest, they may be large enough to have potential climatic significance. It is also plausible that they may have been underestimated as a result of prescribing sea surface temperature and sea ice

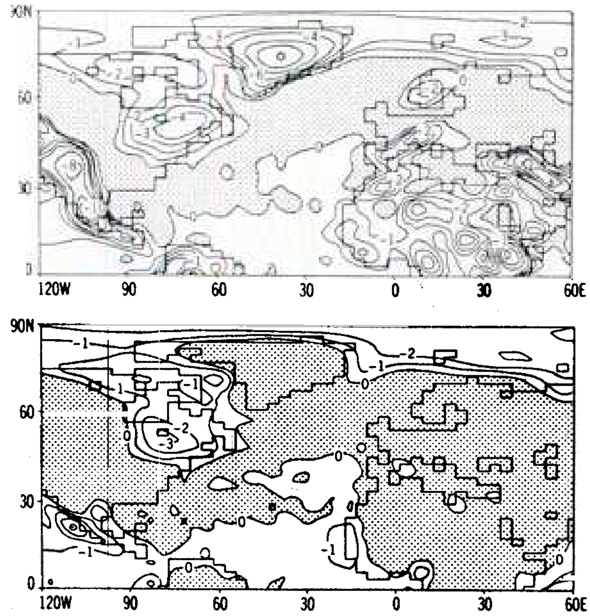

Fig. 11. Spring and summer season (March-August) surface air temperature difference (deg K) between the mountain (M) and no mountain (NM) integrations. Heavy stippling denotes positive values; light stippling temperature decreases of greater than 4 deg K. Top: Unadjusted. Bottom: Adjusted for elevation change.

at their present values in both the M and NM integrations. Kutzbach et al. (1993) report a larger temperature response to orography when these quantities are predicted by the climate model rather than prescribed. This more realistic treatment of the ocean might particularly influence our results for Scandinavia, where the prevailing westerlies blow onshore in both the M and NM integrations thus producing a strong maritime influence in both cases.

Raymo and Ruddiman (1992) have suggested that uplift may have a climatic cooling effect by influencing the atmospheric CO_2 concentration. Noting that variations of atmospheric CO_2 on time scales longer than a million years are determined by a balance between its removal by weathering and its release by volcanism, they hypothesize that uplift can increase the rate of weathering because of orographically-induced heavy rain, exposure of fresh rock to weathering by faulting, and faster runoff due to steeper slopes. While it is important to consider this mechanism as a potential cause of the late Tertiary cooling that set the stage for the periodic glaciations of the Pleistocene, the orographic effects on atmospheric circulation should not be discounted as another possible contributor. Because it occurs in a region where Pleistocene ice sheets are believed to have been initiated, it is plausible that the cooling of a few

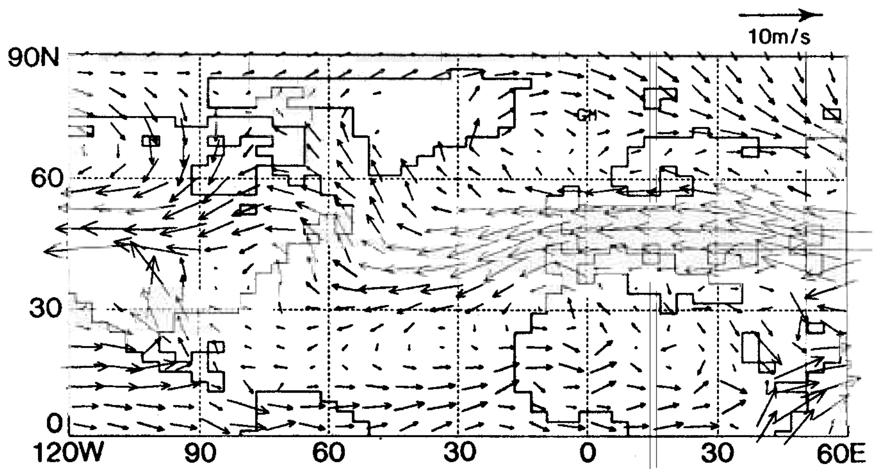

Fig. 12. Vector wind difference at 830 mb level between the mountain (M) and no mountain (NM) integrations. Arrow at upper right corresponds to a magnitude of 10 m/s.

degrees associated with the orographically-induced circulation changes could be climatically significant. A better understanding of the processes which lead to ice sheet initiation and growth is required in order to know if a cooling of this magnitude is indeed an important contributor.

5. PROSPECTS FOR FUTURE RESEARCH

While many climate modeling studies of the interactions between ice sheets and climate have already been performed, many interesting questions remain to be explored. "Snapshot" modeling experiments will continue to be valuable tools in the exploration of these interactions, since they provide a method for exploring the influences of specific processes on climate. The possibilities for additional studies of this kind are many. For example, it has been suggested that as a continental ice sheet becomes larger its further growth may be inhibited by a negative feedback, as colder temperatures gradually deprive it of its moisture supply. Snapshot experiments could be designed to explore this possibility. In addition, many of the earlier studies of glacial climate used the CLIMAP (1981) reconstructions to provide boundary conditions or to evaluate model performance. In some cases, more recent work has suggested a revision of these reconstructions.

For example, Tushingham and Peltier (1991) have used an inverse modeling technique to infer the global distribution of the thickness of continental ice as a function of time for the period since the last glacial maximum. Their results suggest considerably lower elevations for the LGM ice domes than those of the CLIMAP maximum reconstruction, but with a similar horizontal extent. Whether or not the simulated effects of ice sheets on the atmospheric circulation would be sensitive to these revised boundary conditions remains uncertain. Shinn and Barron (1989) studied the sensitivity of climate to ice sheet size by using the maximum and minimum ice sheet reconstructions of Hughes et al. (1981). While they found the split flow around the Laurentide ice sheet to be sensitive to ice sheet size, it is difficult to separate the effects of height and horizontal extent. Updated boundary conditions provided by the Paleoclimate Model Intercomparison Project (Joussaume, private communication) will allow climate modelers to reevaluate the effects of continental ice on glacial climate, and thus may provide some answers to this and related questions.

Modeling the multiple interactions among continental ice sheets and other components of the climate system is also becoming more feasible. Manabe (1989) has used an atmospheric GCM coupled to a ocean circulation model to explore the response of the coupled atmosphere-ocean system to glacial boundary conditions. He suggested that a realistic simulation of the modern thermohaline circulation may be necessary for the simulation of glacial-to-interglacial changes in the atmosphere-ocean system. A further step is the coupling of a climate model with a three-dimensional ice sheet model. Verbitsky and Oglesby (1992) have moved in this direction by asynchronously coupling the NCAR Community Climate Model to a model of the ice sheet-asthenosphere system to study the effect of atmospheric CO_2 on continental glaciation. These early ventures are examples of a more comprehensive approach to modeling the climate system that is likely to receive greater attention in the future. Subsequent efforts of this kind may allow even greater understanding of the interactions between ice sheets and the atmosphere-ocean system.

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