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THE CLIMATE OF TEN THOUSAND YEARS AGO: A NUMERICAL SIMULATION

J. ADEM*

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RESUMEN

Para simular el clima de hace 10 000 años se aplica un modelo termodinámico que incluye el ciclo anual, una capa oceánica mezclada y una capa de hielo y nieve variable.

Se demuestra que en latitudes bajas las anomalías de insolación debidas a las variaciones orbitales fueron el factor principal que produjo las diferencias con respecto al clima presente. Sin embargo, además de las anomalías de insolación, las capas permanentes de hielo también afectaron el clima de hace 10 000 años en latitudes medias y altas.

En el verano, el promedio de la temperatura calculada en la superficie de los continentes del Hemisferio Norte es 1.9°C más caliente que en la actualidad y en las otras estaciones más frío, con una diferencia de −2.1°C en invierno. El promedio anual de la diferencia es de −0.7°C.

La temperatura de la superficie del océano permanece abajo de los valores actuales durante todo el año, con valores promedio de −0.8 en invierno, −0.2 en verano y −0.5°C para todo el año.

Se demuestra que cuando se prescriben los valores actuales de la temperatura de la superficie del océano, se obtiene un clima más caliente, con una anomalía de temperatura promedio de la superficie del continente igual a 2.2, −1.6 y −0.3°C para verano, invierno y promedio anual respectivamente.

Se lleva a cabo un estudio sobre la importancia de la incorporación en el modelo del ciclo anual, una capa oceánica mezclada y una capa de hielo y nieve variable.

* *Centro de Ciencias de la Atmósfera, UNAM, México 04510, D. F. MEXICO.*

ABSTRACT

A thermodynamic model that includes the annual cycle, an ocean mixed layer and a variable cryosphere is applied to simulate the climate of 10 000 years ago.

It is shown that in lower latitudes the insolation anomalies due to the orbital variations were the main factor that produced the departures from the present climate. However, besides the insolation anomalies, the permanent ice sheets also affected the climate of 10 kyr BP in middle and higher latitudes.

The average computed land surface temperature in the Northern Hemisphere is 1.9°C warmer than present summer and colder during the other seasons, with an anomaly as large as −2.1°C in winter. The annual average anomaly being −0.7°C.

The computed surface ocean temperature remains below the present values during the entire year with an average value of −0.8 in winter, −0.2 in summer and −0.5°C for the whole year.

It is shown that when present values of surface ocean temperature are prescribed, a warmer climate is obtained, with average land surface temperature anomalies equal to 2.2, −1.6 and −0.3° for summer, winter and annual values respectively.

A study on the importance of the inclusion in the model of the annual cycle, the ocean mixed layer and the variable cryosphere is carried out.

INTRODUCTION

In the last few years, data to study the climates of the past have become increasingly available (CLIMAP, 1976; Berger, 1978; Denton and Hughes, 1981) and several experiments to simulate the corresponding climates have been carried out (among others: Gates, 1976, Kutzbach and Otto-Bliesner, 1982; Adem, 1981, 1982; Adem *et al.*, 1984). In all these experiments the surface ocean temperature has been prescribed.

In this paper an attempt is made to compute the surface ocean temperature deviations from present values and an evaluation is made of their effects in the solution. The case chosen for this study is the climate of ten thousand years ago ((10 kyr BP), in which according to Berger (1978) there were strong positive deviations of the insolation with respect to present values in the summer and negative deviations during the rest of the year. Because of this change of sign in the anomalies of the insolation, this forcing function enables the inter-seasonal effects of the mixed ocean layer to be shown in the solution.

It is believed that the ocean temperatures at this period were very close to present values. We will, therefore, also carry out computations prescribing the present surface ocean temperatures, and a comparison with the case in which the effect of the computed ocean temperature anomalies is included.

THE MODEL AND THE DATA USED

The model used is the latest version of the thermodynamic model described in detail in a recent paper (Adem, 1982). It consists of an atmospheric layer 10 km high, an oceanic layer of a depth of 50 to 100m, and a continental layer of negligible depth. The model also includes a layer of clouds and a layer of snow and ice, whose horizontal extent are computed internally.

The basic predicting equation is the conservation of thermal energy which applied to the atmospheric layer and to the ocean (or continent) layer yields two equations which contain as variables the mean atmospheric temperature (T_m) and the surface temperature (T_s) as well as the heating and the transport terms.

The other conservation laws are used diagnostically, together with semi-empirical relations, to parameterize the heating and transport components. These parameterizations supply additional equations which, combined with the thermal energy equations, give rise to a system of simultaneous equations. This is solved with an implicit integration method, yielding, besides the temperatures, the heating functions and the anomalies of wind.

The parameterizations of the heating and transport terms are those described by Adem (1982), except for the modifications used by Adem and Garduño (1984) in order to incorporate the conservation of water vapor in the model.

The equations and the variables are averaged over a month, so that the horizontal transport of heat in the atmosphere by transient eddies is parameterized using a horizontal exchange coefficient equal to 3×10^6 $m^2 sec^{-1}$.

The snow-ice boundary is carried out as a variable by assuming that it coincides with the 0°C computed surface isotherm. This is accomplished by an adjusting process between surface albedo and surface temperature by which at each grid point an albedo for snow-ice cover is assigned when the computed surface temperature is lower or equal to 0°C, and an albedo for no snow-ice on the ground is assigned when the surface temperature is larger than 0°C, as is described by Adem (1981). The adjusting process converges rapidly due to the snow-ice temperature feedback.

Starting in August, when the snow-ice cover is minimal, the model is iterated month by month until the difference between the computed anomaly of the surface temperature, each month of the last year and the same month of the previous year of the run is smaller or equal to 0.01°C.

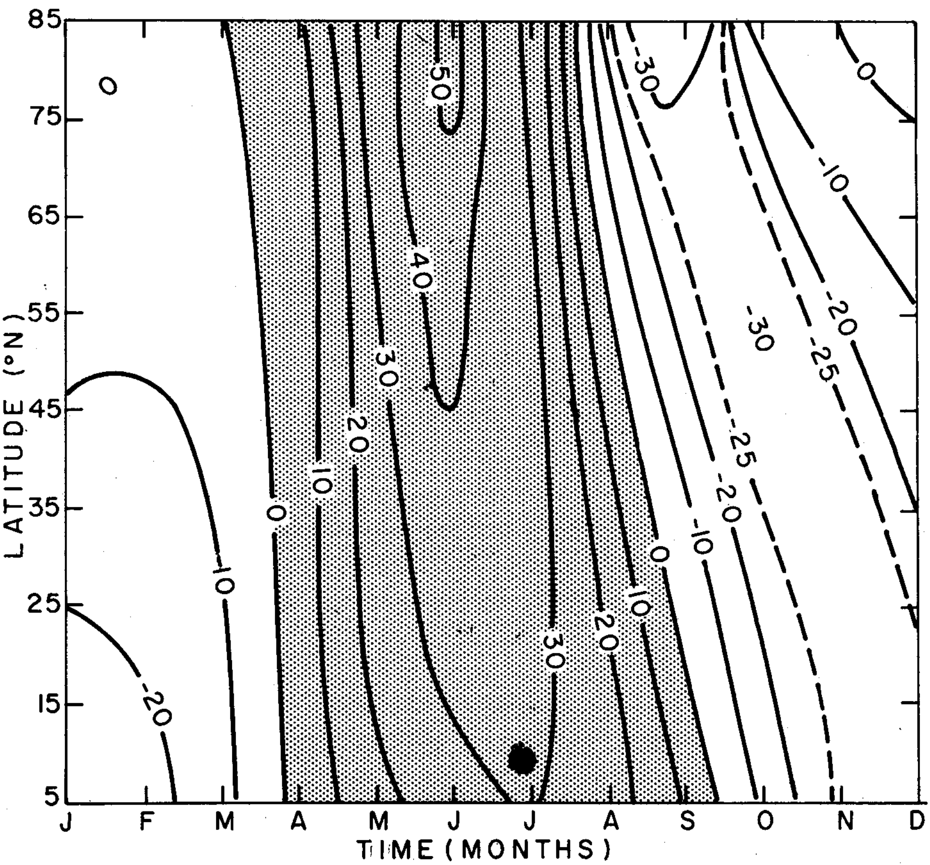


Fig. 1. The insolation monthly departure from present climate for 10 kyr BP, after Berger, in Watts per square meter.

The following data corresponding to the climate of 10 kyr BP are used:

a) *The insolation monthly departures from present climate* given by Berger (1978) and which are shown in Fig. 1.

b) *The horizontal extent of the permanent ice sheets that existed at that time,* as given by Denton and Hughes (1981) which is shown in Fig. 2. It is included in the computations as the minimum snow-ice extent allowed in the model, in a similar way as was done for the case of 18 kyr BP (Adem, 1981).

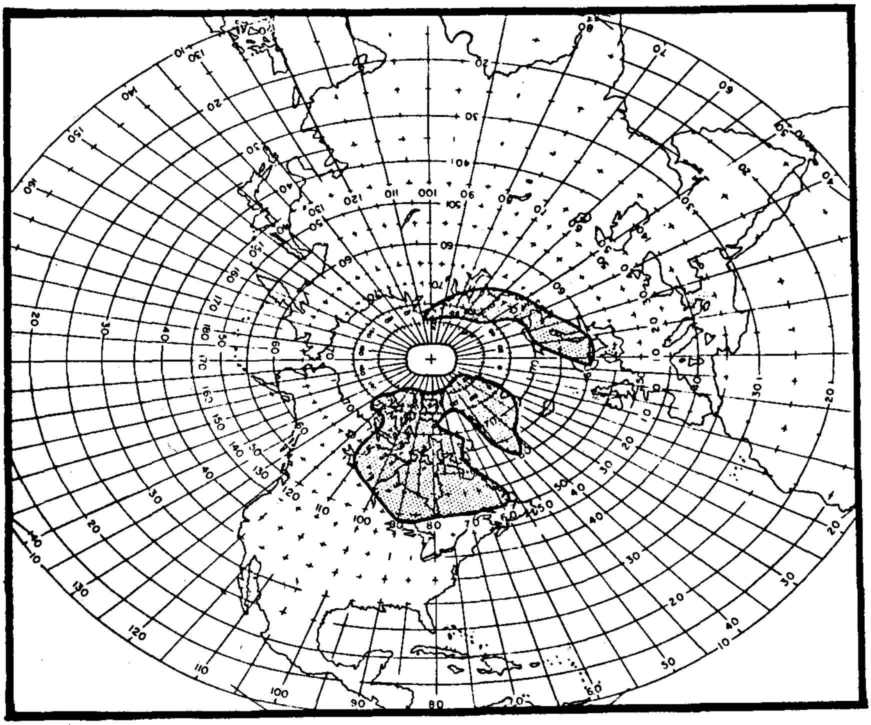
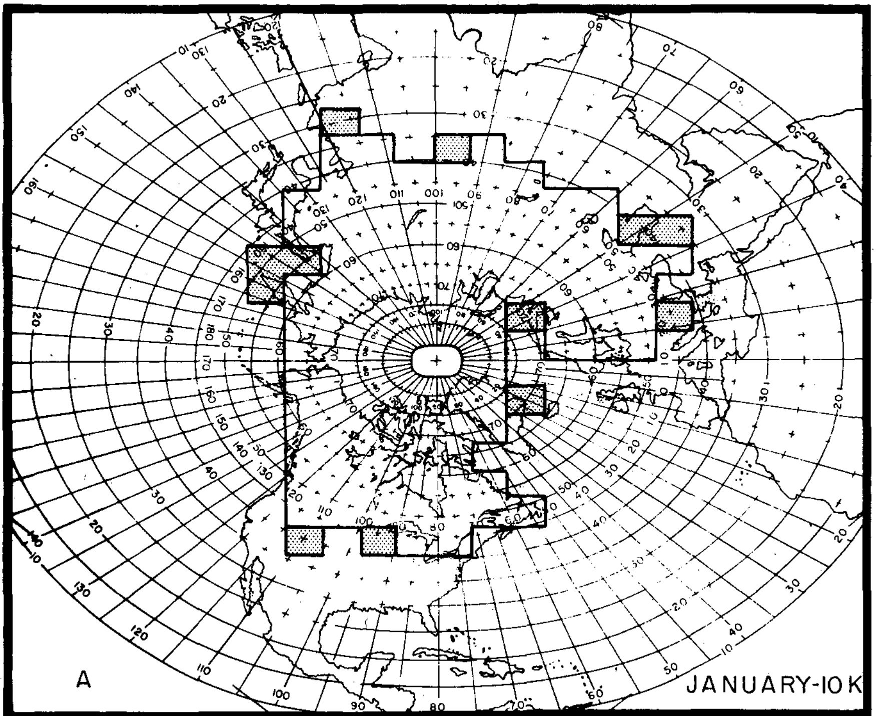


Fig. 2. Ice sheets boundaries during 10 kyr BP, after Denton and Hughes.

THE CLIMATE OF TEN THOUSAND YEARS AGO

As is usual in the applications of this model, first the present climate is simulated, and then the climate for 10 kyr BP. The simulation for the present climate has been shown in a previous paper (Adem, 1982). The results for 10 kyr BP are shown here.

Fig. 3 shows a comparison of the computed snow-ice boundary for



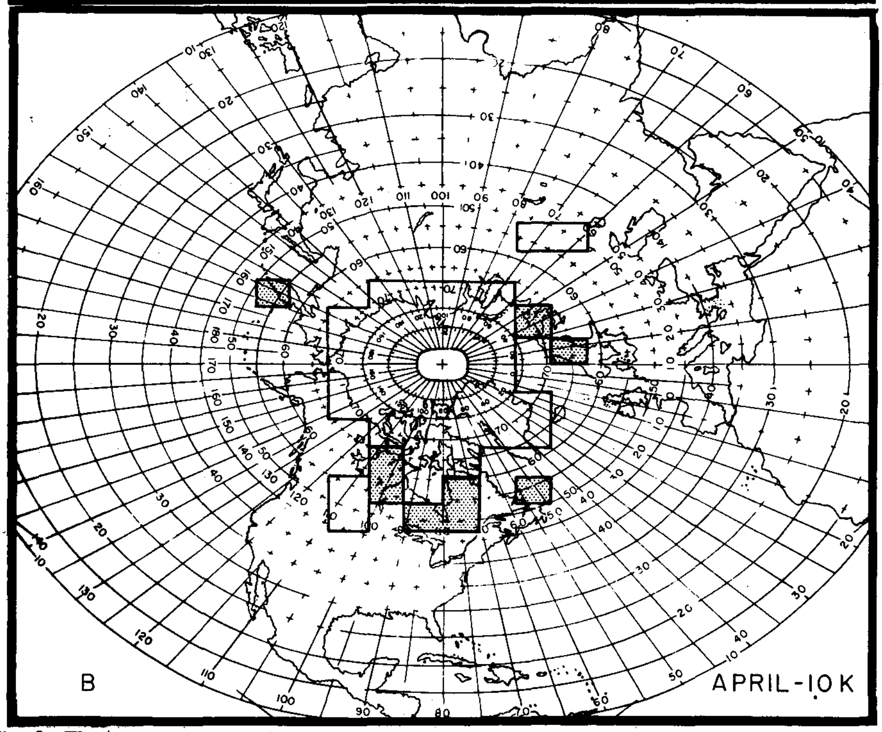


Fig. 3. The computed snow-ice boundary for January (A), April (B), July (C), and October (D) of 10 000 years ago. The shaded regions are the differences with respect to the present computed boundary.

present and for 10 kyr BP. The shaded areas represent the deviations of 10 kyr BP from present values. Part A, B, C and D correspond to January, April, July and October respectively. A comparison of Fig. 3 with Fig. 1 shows that the largest anomalies (increases) of the snow boundary occur in the fall, when the negative anomalies of radiation are the largest. The anomalies in July correspond to the permanent ice sheets that existed at 10 kyr BP.

Fig. 4 shows the computed surface temperature anomalies (departures from present climate) in ^{o}C. Part A, B, C and D correspond to January, April, July and October respectively. The anomalies are larger in the continents than in the oceans. The stronger negative anomalies in the continents are due to the snow-ice cap anomalies. The strong positive anomalies for July over the continents are due to the positive anomalies of insolation at this time of the year.

Fig. 5 shows the anomalies of the mean tropospheric temperature. Parts A, B, C and D correspond to January, April, July and October respectively. Comparison of figures 5 and 4 shows that there is a strong correspondence between the surface ground temperature anomalies and the mean tropospheric temperature anomalies, however, the mean tropospheric temperature anomalies are smoother.

Except for July, the temperature anomalies are negative. In July over the continents there are strong positive anomalies due to the insolation anomalies, except in the region of permanent ice, where the largest negative anomalies are located.

Fig. 6 shows the zonally averaged values of the surface temperature for winter (dashed line), spring (dashed-dotted line), summer (solid line) and fall (dotted line).

In order to study the seasonal cycle of the solution, the average values over the whole region of integration (which includes the Northern Hemisphere, except lower latitudes below 10^{o}N) will be considered.

In Fig. 7 the solid line shows the insolation anomaly for 10 kyr BP as a function of the time of the year. The abscissa is the time in months and the ordinate on the left side, the insolation anomaly in W/m^2. In the same figure the dotted line shows the average of the com-

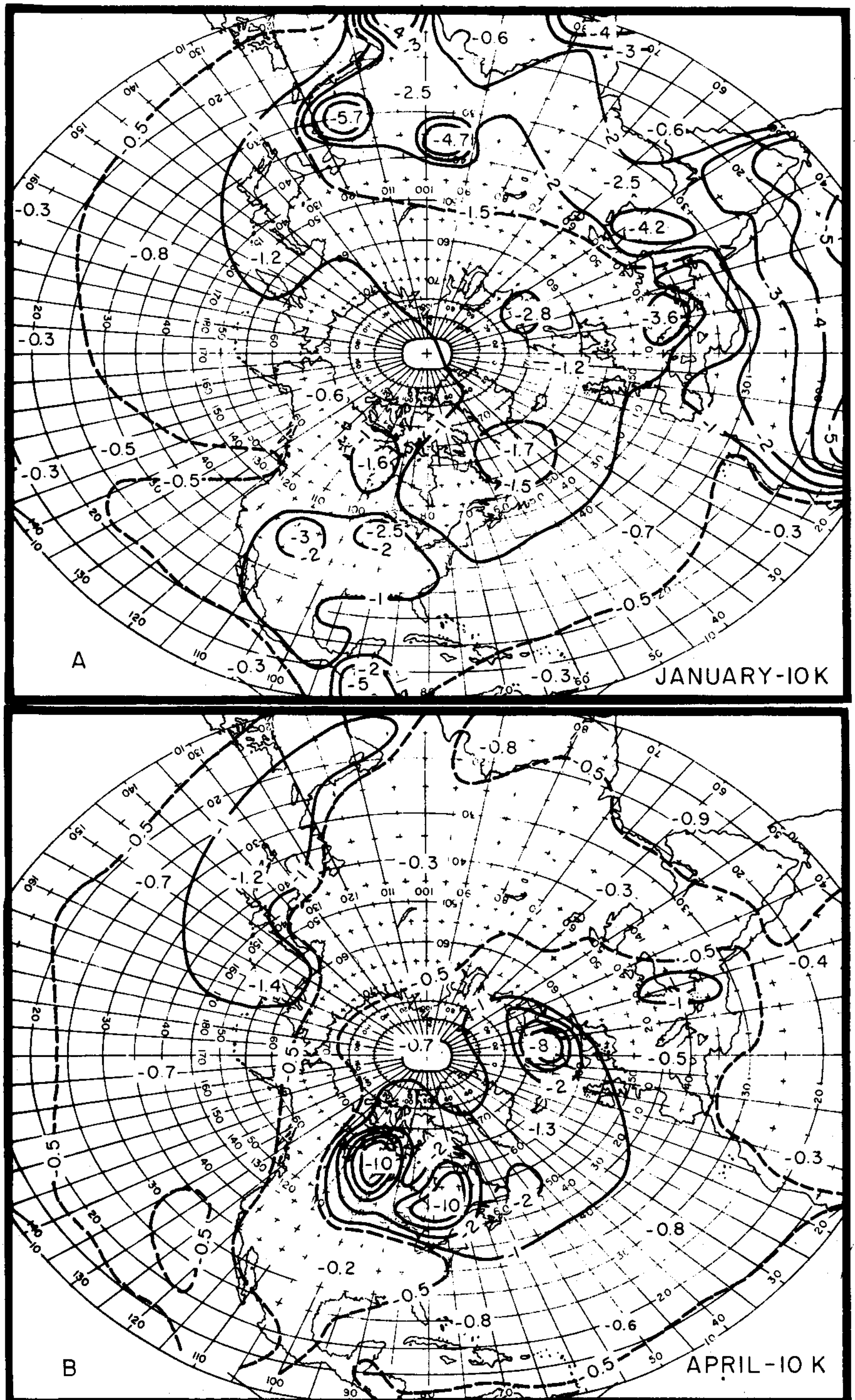
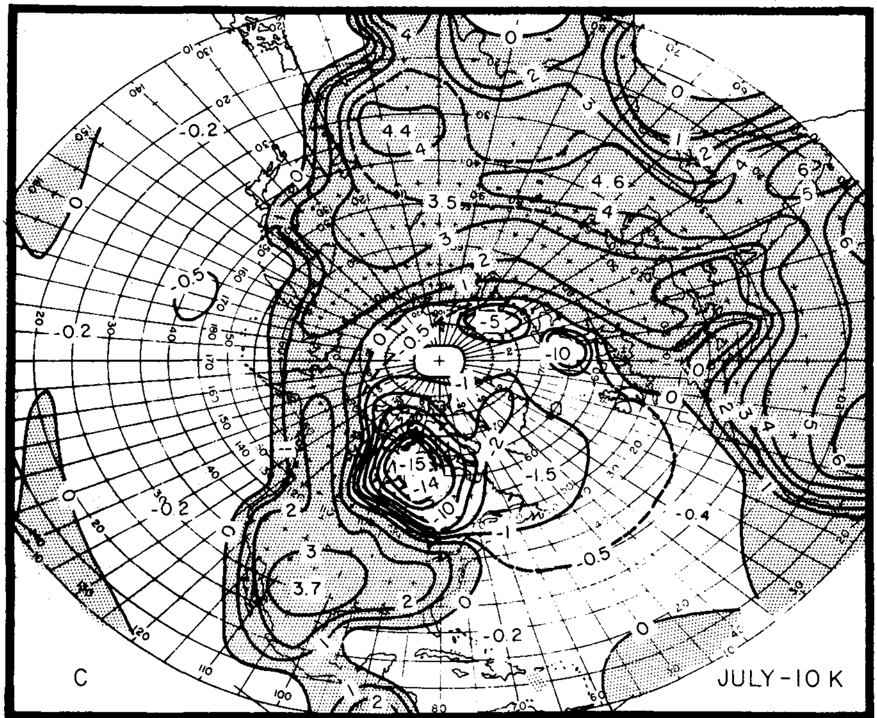
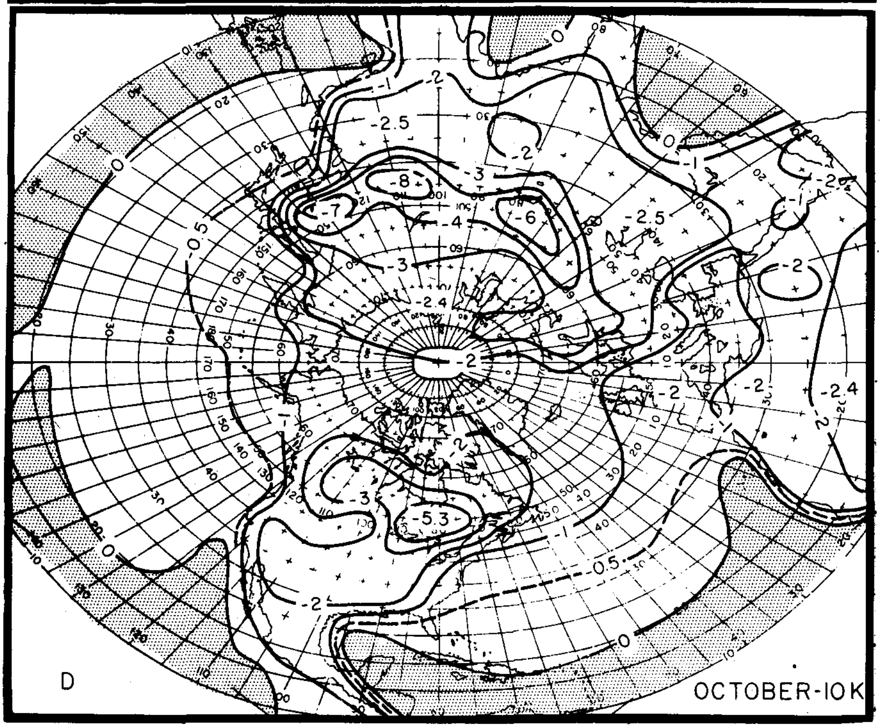


Fig. 4. Computed surface temperature anomalies of 10 kyr BP for January (A), April (B), July (C) and October (D) in degrees Celsius.


C
JULY-10 K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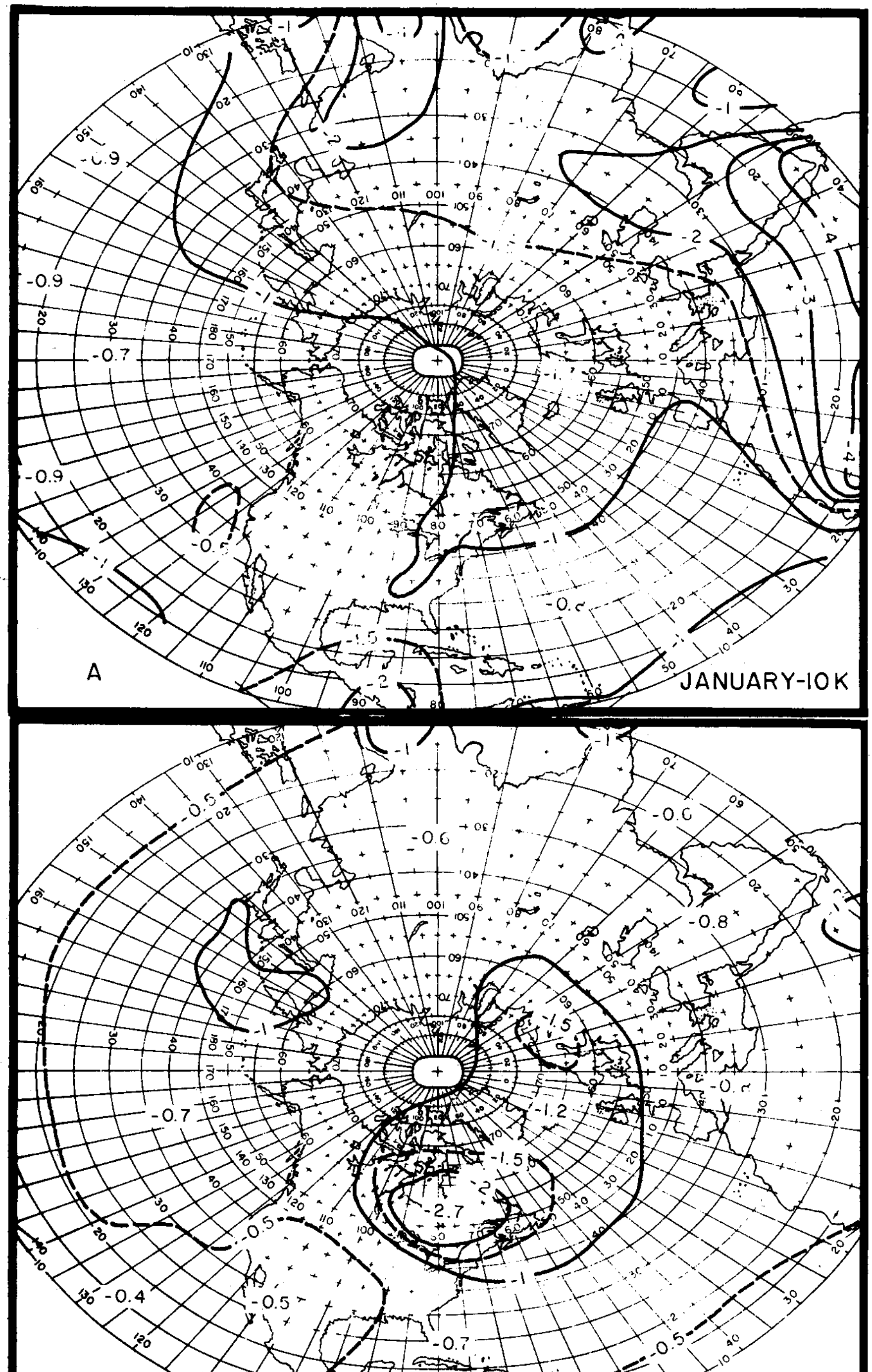
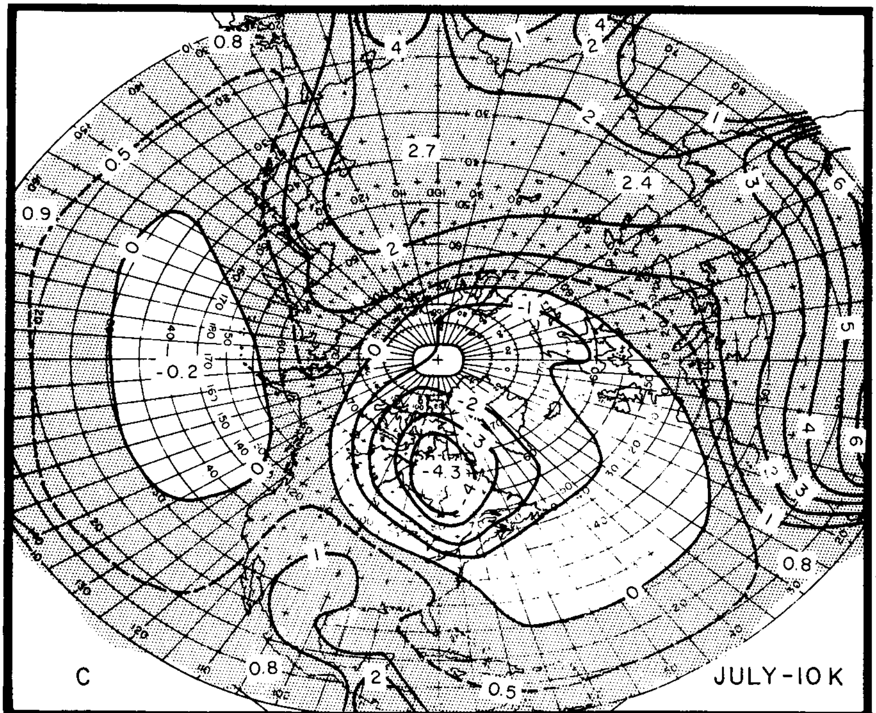
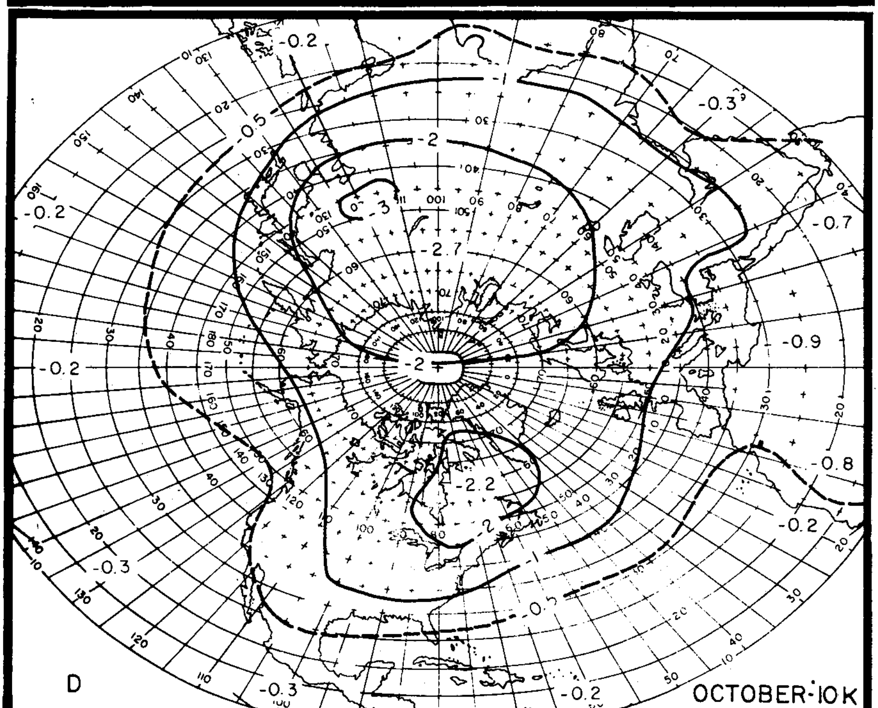


Fig. 5. Computed mean tropospheric temperature anomalies for 10 kyr BP for January (A), April (B), July (C) and October (D), in degrees Celsius.


C
JULY-10K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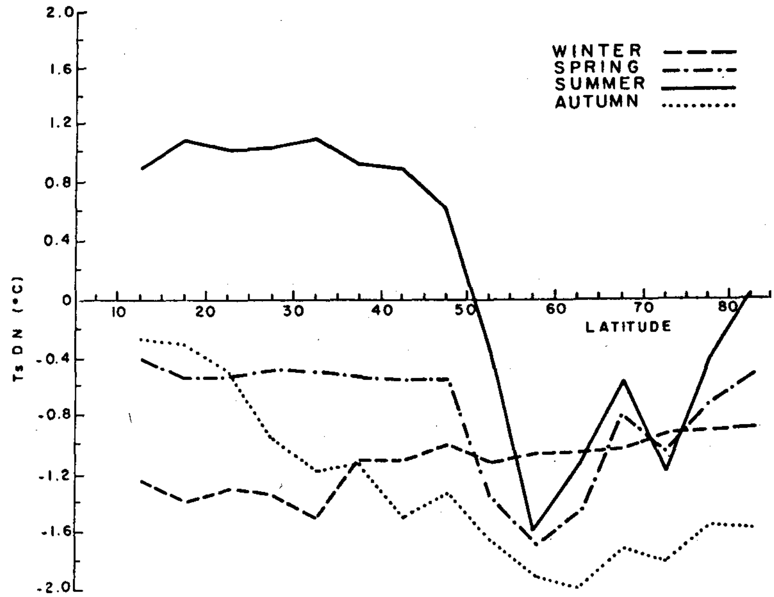

Fig. 6. Zonally averaged values of the computed ground temperature anomalies, in degrees Celsius, for winter (dashed line), spring (dashed-dotted line), summer (continuous line), and autumn (dotted line) of 10 000 years ago.

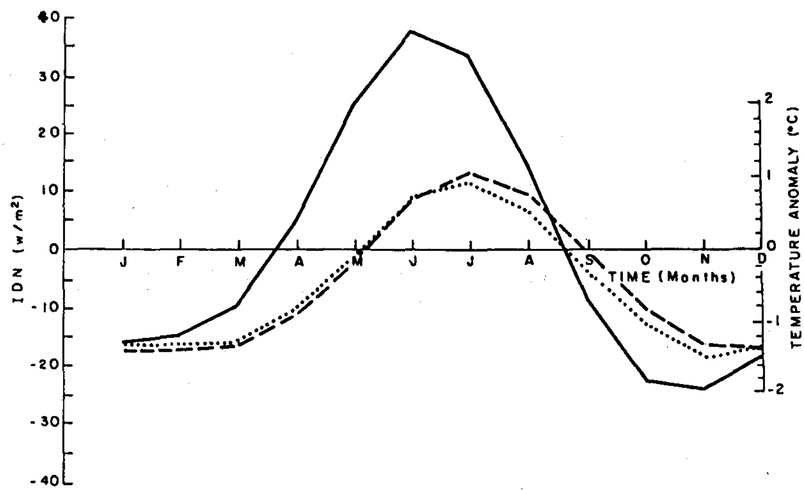

Fig. 7. Average over the total region of integration of the computed ground temperature anomalies (dotted line), the computed mean tropospheric temperature anomalies (dashed line) and the insolation anomalies (continuous line) of 10 000 years ago. The abscissa is the time in months. The ordinate for temperatures (on the right side) is in degrees Celsius and for the insolation (on the left side) is in Watts per square meter.

puted anomalies of surface temperature and the dashed line, the mean tropospheric temperature, where the corresponding ordinate, shown on the right side, is in °C. This figure shows that there is a lag in the time of the change of the sign of the computed temperature anomalies with respect to the change of the sign of the anomalies of the insolation. In spring, this lag is of about one and a half month for both temperature anomalies, and at the beginning of autumn of about half of a month for the mean tropospheric temperature and negligible for the surface temperature anomalies. Furthermore, the largest positive anomaly is for the insolation in June, while for the computed temperatures it is in July. It will be shown in the next section that this lag is due to the effect of the storage of heat in the oceans, which is included in the model through the equation of conservation of thermal energy applied to the ocean mixed layer (Adem, 1982). In this way the surface ocean temperature anomaly is a variable computed in the model which has strong interactions with the other climate variables and strongly affects the solution.

EFFECT OF THE OCEAN MIXED LAYER

In the computations shown above, an ocean mixed layer of 60 m has been used. In this section a study is carried out about the effect of varying the depth of the ocean layer in the results.

Fig. 8 shows the average value of the surface temperature anomalies for different depths of the ocean mixed layer, used in the model. The solid, dotted and dashed-dotted lines correspond to solutions of 100 m, 60 m, and 25 m respectively. In the three cases the anomalies follow

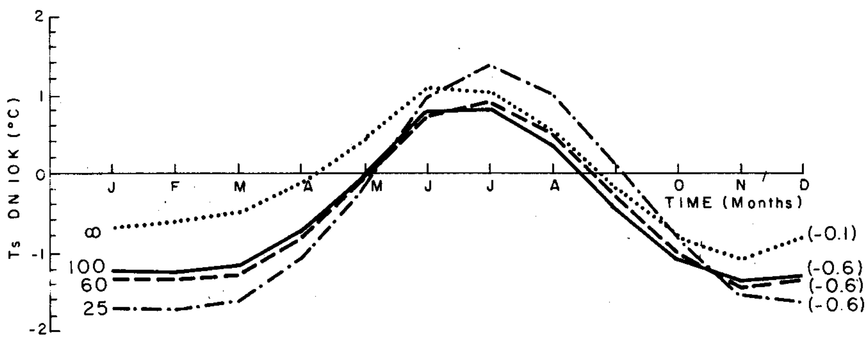

Fig. 8. Average over the total region of integration of the ground temperature anomalies for 10 kyr BP, computed with a model that has an ocean mixed layer of 25 m (dashed-dotted line), 60 m (dashed line) and 100 m (solid line). and with a model in which present ocean temperatures are prescribed (dotted line). The abscissa is the time in months, and the ordinate the temperature anomaly in degrees Celsius.

the same pattern through the year, but their size decreases as the depth of the mixed layer increases. However, the average for the whole year, shown in parentheses to the right of each curve is the same and equal for the three cases to -0.6^{o}C.

The dotted line corresponds to a solution when the ocean temperature is prescribed to its present values. In this case the annual average is equal to -0.1^{o}C. Comparison of these solutions shows that the inclusion of the ocean mixed layer and the corresponding computation of ocean temperature anomalies, yields solutions which have a lag with respect to the one with prescribed ocean temperature. Furthermore the annual average for the case when the surface ocean temperatures are prescribed is much smaller than the ones with the inclusion of the ocean mixed layer.

For mean tropospheric temperature we obtain similar curves, as those of Fig. 8, but in this case the annual averages are equal to -0.5^{o}C for the 3 cases of depth of mixed layer, and equal to -0.1 for the case of prescribed zero ocean temperature anomalies.

To analyse the effect of the ocean mixed layer in more detail we show in Fig. 9, separately, the average computed surface temperature in the oceans (A) and in the continents (B). Fig. 9A shows the effect of the depth of the mixed layer on the annual cycle of the surface ocean temperature. A layer of 25 m has stronger seasonal changes than a layer of 60 m, and the solution of 100 m is practically the same as the one for 60 m. It is interesting that for a depth of 100 m the ocean temperature anomalies for the whole year are below normal, even in summer when the radiation anomaly is strongly positive. In Fig. 9A the dotted line corresponds to the case of prescribing present ocean temperature (zero anomaly).

Fig. 9B shows that the average of the continental ground temperature has larger variability throughout the year than the average over the oceans and that the effect of the depth of mixed layer is similar than for the oceans but not as strong as in that case.

For the mean tropospheric temperature anomalies we have similar effect as for the surface temperature anomalies. However, the mean over the oceans of the tropospheric temperature anomalies for the case

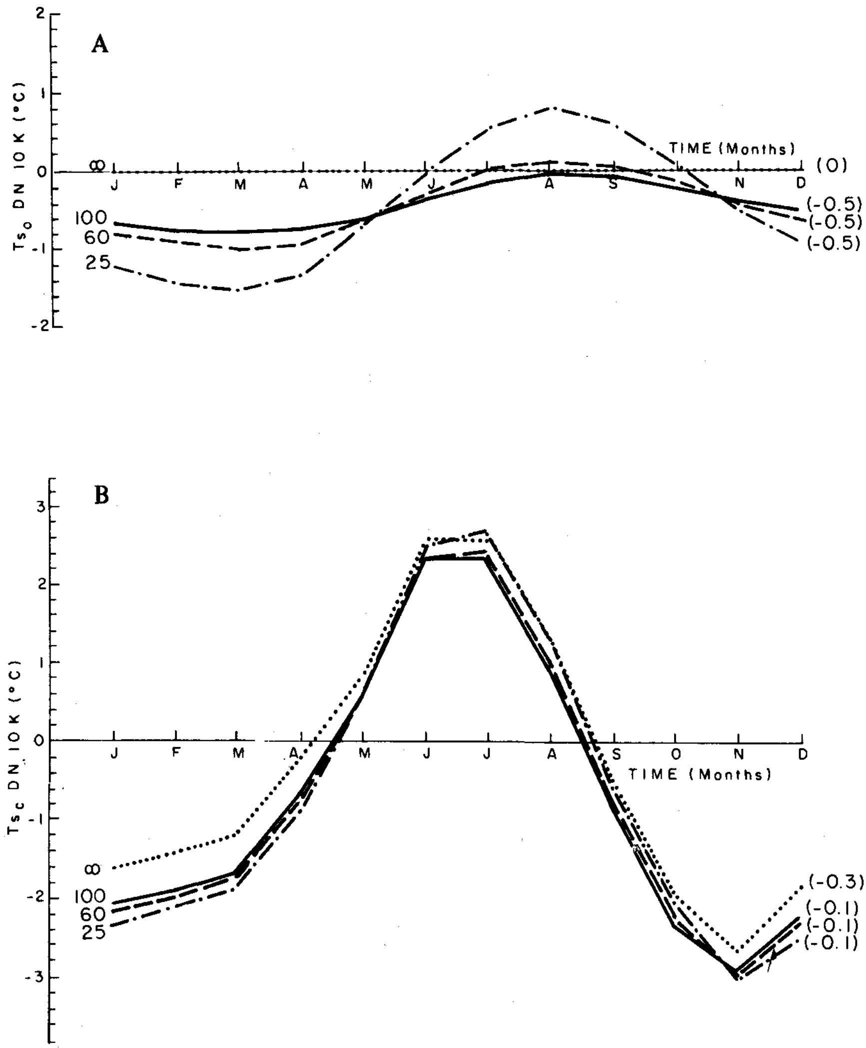

Fig. 9. Average over the total region of integration of the surface ocean temperature anomalies (A), and surface land temperature anomalies (B), computed with a model that has an ocean mixed layer of 25 m (dashed-dotted line), 60 m (dashed line) and 100 m (solid line); and with a model in which present ocean temperatures are prescribed (dotted line). The abscissa is the time in months, and the ordinate the temperature anomaly in degrees Celsius.

of a mixed layer of 100 m are positive from June to August.

Table 1 shows the average seasonal and annual values of the surface and mean tropospheric temperature anomalies for the Northern Hemisphere (NH), as well as for the oceans (NHO) and continents (NHC) separately. The values of the table correspond to the case when a mixed ocean layer of 60 m is used in the solution.

Table 1

Computed temperature departures from present values for 10 kyr BP, when a mixed ocean layer of 60 m depth is included in the model.

	Surface temperature			Mean tropospheric temperature		
	NH	NHO	NHC	NH	NHO	NHC
Winter	−1.4	−0.8	−2.1	−1.4	−1.1	−1.9
Spring	−0.8	−0.9	−0.6	−0.8	−0.8	−0.8
Summer	0.7	−0.2	1.9	0.8	0.3	1.6
Autumn	−0.9	−0.2	−2.0	−0.1	−0.4	−1.2
Annual	−0.6	−0.5	−0.7	−0.5	−0.5	−0.5

Table 2 is similar to Table 1 except that it shows the values corresponding to the solution when ocean temperatures are prescribed as present values.

Table 2

Computed departures from present values for 10 kyr BP, when present values of ocean temperature are prescribed.

	Surface temperature			Mean tropospheric temperature		
	NH	NHO	NHC	NH	NHO	NHC
Winter	−0.7	0	−1.6	−0.8	−0.4	−1.3
Spring	0	0	−0.1	−0.1	0	−0.2
Summer	0.9	0	2.2	1.0	1.5	1.8
Autumn	−0.7	0	−1.7	−0.5	−0.2	−0.9
Annual	−0.1	0	−0.3	−0.1	0	−0.1

The differences between the values of Table 1 and the corresponding values of Table 2 are shown in Table 3. These differences show that the

Table 3

The values of Table 1 minus the values of Table 2. (Change of temperature due to the inclusion of an ocean mixed layer in the model).

	Surface temperature			Mean tropospheric temperature		
	NH	NHO	NHC	NH	NHO	NHC
Winter	−0.7	−0.8	−0.5	−0.6	−0.7	−0.6
Spring	−0.8	−0.9	−0.5	−0.7	−0.8	−0.6
Summer	−0.2	−0.2	−0.3	−0.2	−0.2	−0.2
Autumn	−0.2	−0.2	−0.3	−0.2	−0.2	−0.3
Annual	−0.5	−0.5	−0.4	−0.4	−0.5	−0.4

annual temperature anomalies for oceans and continents are about half a degree Celsius colder for the solution in which the ocean temperature anomaly is allowed to vary. The smallest differences occur in summer and autumn (−0.2 to −0.3°C), and the largest in winter and spring (−0.8 to −0.9°C).

CONTRIBUTIONS OF THE INSOLATION ANOMALIES AND THE PERMANENT ICE SHEETS

The two forcing factors in the model are the insolation anomalies and the permanent ice sheets that existed ten thousand years ago. In order to evaluate the importance of these two forcing factors, an experiment was carried out using the same model as in section 3 but in which the permanent ice sheets were taken as they exist at present and only insolation anomalies were included in the experiment.

Fig. 10 shows the computed surface temperature anomalies for January (A) and July (B). Comparison with the corresponding maps (A and C) of Fig. 4 shows, as expected, that the stronger effect due to the ice sheets occurs in higher latitudes, and the weakest effect in lower latitudes. The effect on the ocean temperatures is also important.

The zonally averaged values of the computed surface temperature anomalies are shown in Fig. 11, where the thick continuous line corresponds to summer and the thick dashed line to winter. The corresponding values for the experiment in which, besides the insolation anomalies, the permanent ice sheets are included, are shown with thin continuous and dashed lines respectively. Comparison of these results shows that the two forcings are important.

The two solutions are similar in lower latitudes where the insolation anomalies are the main factor. However, the effect of the ice sheets is very important in middle and higher latitudes, where the difference between the two solutions is of several degrees Celsius and the anomalies become negative due to the existence of the ice sheets. The zonally averaged values of the albedo anomaly due to the permanent ice sheets are shown in the same Fig. 11 by the dotted line. The corresponding ordinate is shown to the right in percent. The zonally averaged albedo anomaly is located from the band 50-55 to 75-80 degrees of latitude, and reaches values as large as 11 percent. However, it is of interest to

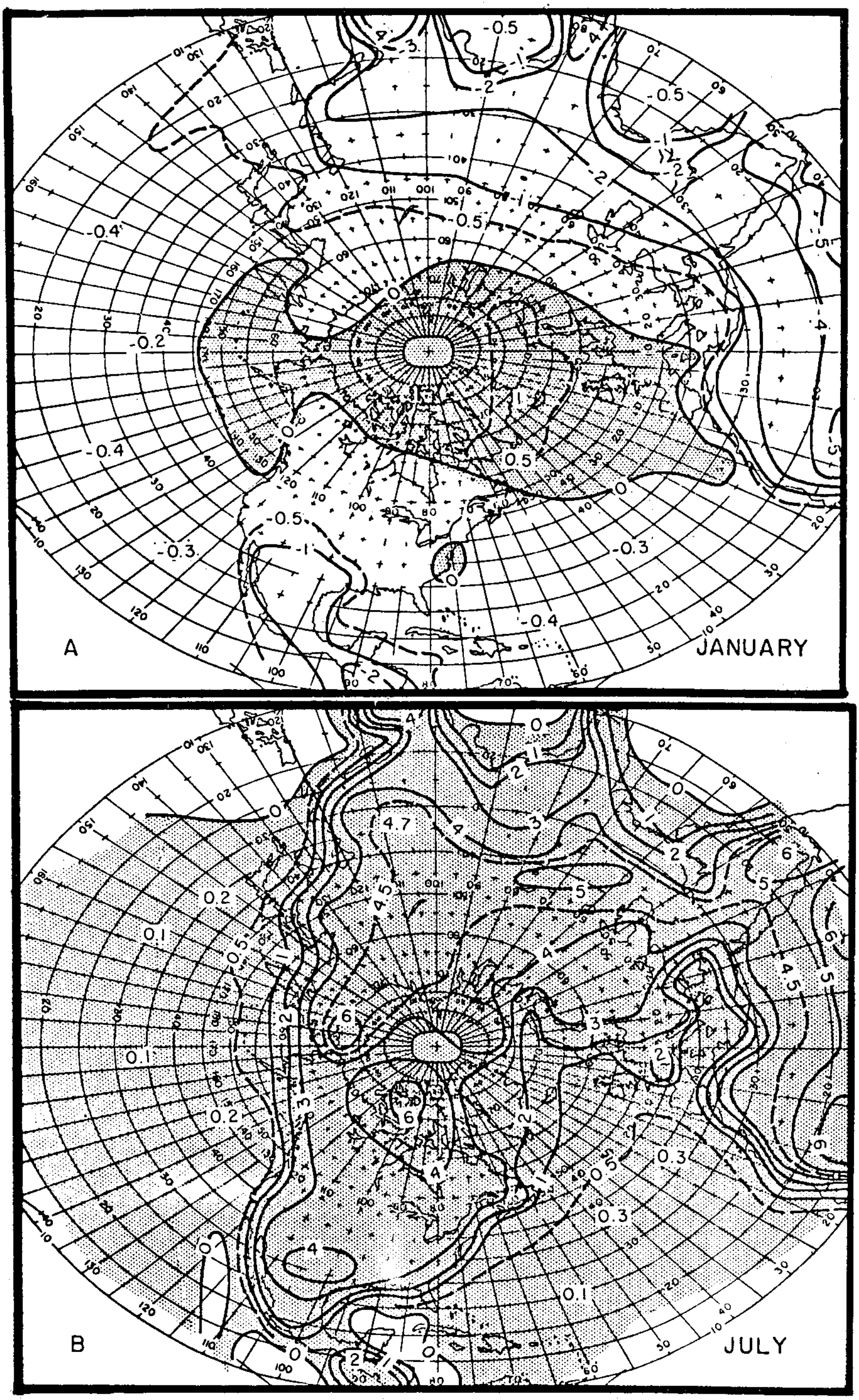

Fig. 10. The computed surface temperature anomalies for 10 kyr BP when only insolation anomalies are included and the effect of the permanent ice sheets is neglected, for January (A), and July (B), in degrees Celsius.

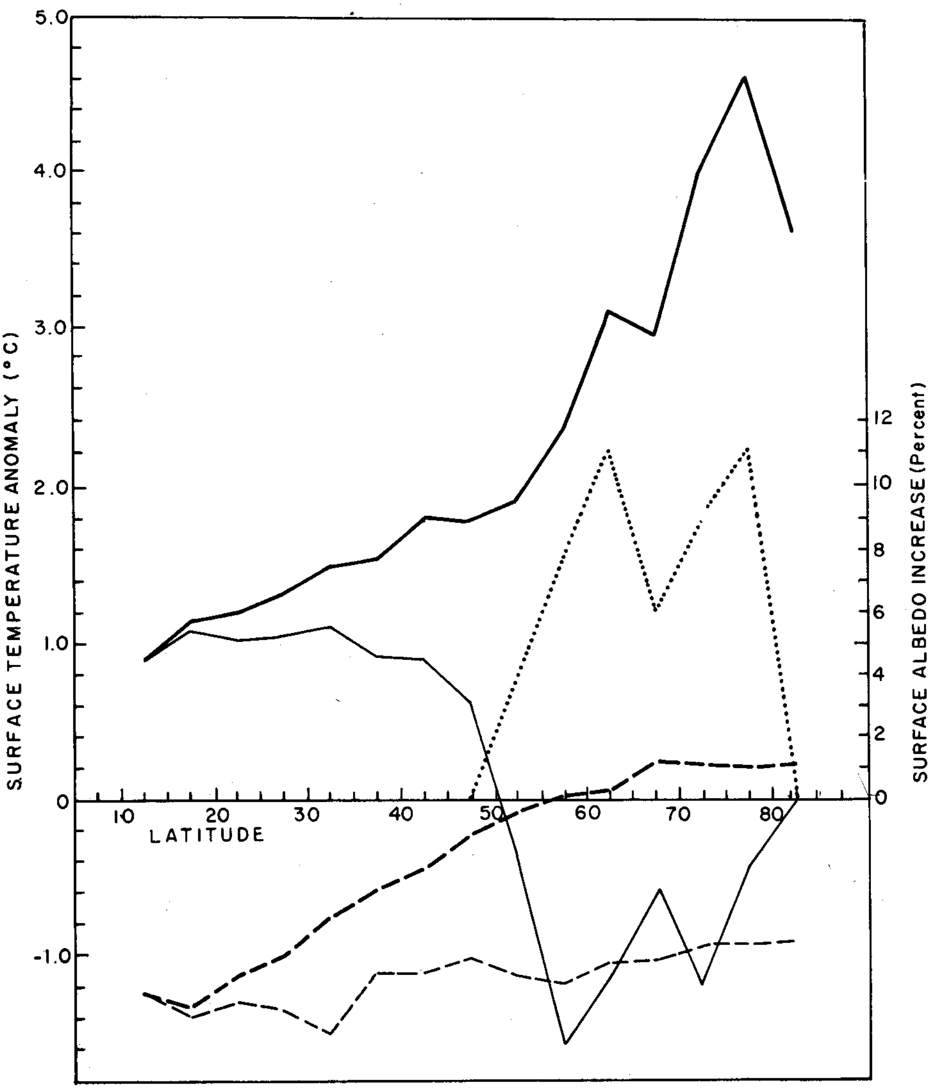

Fig. 11. Zonally averaged values of the computed surface temperature for 10 kyr BP. Continuous lines: summer. dashed lines: winter. The thick lines correspond to the case when only the radiation anomaly is included as external forcing; and the thin lines, to the case when besides the radiation anomaly, the effect of the ice sheets is included. The dotted line is the zonally averaged albedo anomaly due to the ice sheets, the corresponding ordinate is to the right in percent.

point out, that the average albedo anomaly over the whole region of integration is only 1 percent.

Table 4 shows, for the case when the ice sheets are neglected, the average seasonal and annual values of the surface and mean tropospheric temperature anomalies for the Northern Hemisphere (NH), as well as for the oceans (NHO) and continents (NHC) separately.

Table 4

Computed temperature departures from present values for 10 kyr BP, when the ice sheets are neglected.

	Surface temperature			Mean tropospheric temperature		
	NH	NHO	NHC	NH	NHO	NHC
Winter	−0.7	−0.2	−1.4	−0.8	−0.6	−1.1
Spring	0	−0.4	−0.5	−0.1	−0.3	0.2
Summer	1.6	0.5	3.5	1.7	0.9	2.8
Autumn	−0.4	0.2	−1.2	−0.1	0	−0.3
Annual	0.1	0	0.3	0.2	0	0.4

Table 5 shows the differences between the values of Table 1 and those of Table 4, which are the temperature changes due to the effect of the ice sheets. There is an annual decrease of 0.7°C in the Northern Hemisphere due to the presence of the permanent ice sheets; and the effect is important for all the seasons, in the continents as well as in the oceans.

Table 5

The values of Table 1 minus the values of Table 4 (temperature change due to the effect of the ice sheets).

	Surface temperature			Mean tropospheric temperature		
	NH	NHO	NHC	NH	NHO	NHC
Winter	−0.7	−0.6	−0.7	−0.6	−0.5	−0.8
Spring	−0.8	−0.5	−1.1	−0.7	−0.5	−1.0
Summer	−0.9	−0.7	−1.6	−0.9	−0.6	−1.2
Autumn	−0.5	−0.4	−0.8	0	−0.4	−0.8
Annual	−0.7	−0.5	−1.0	−0.7	−0.5	−0.9

COMPARISON WITH OTHER SIMULATIONS

In the above computation the complete annual cycle is simulated with time steps of one month, so that the interseasonal effect is included. Furthermore, the snow-ice boundary is a variable in the computations and is associated with the snow-ice temperature feedback. It is interesting to compare the results with those obtained previously by Adem *et al* *al.* (1984) with a simpler model in which the solution for summer was obtained directly using the averaged anomaly of radiation for this season (June, July and August), without any interaction with the anomalies in the other seasons of the year. Furthermore the Denton and Hughes (1981) ice boundaries were used and kept fixed, and the present values of ocean temperatures were prescribed. In Fig. 12 are shown

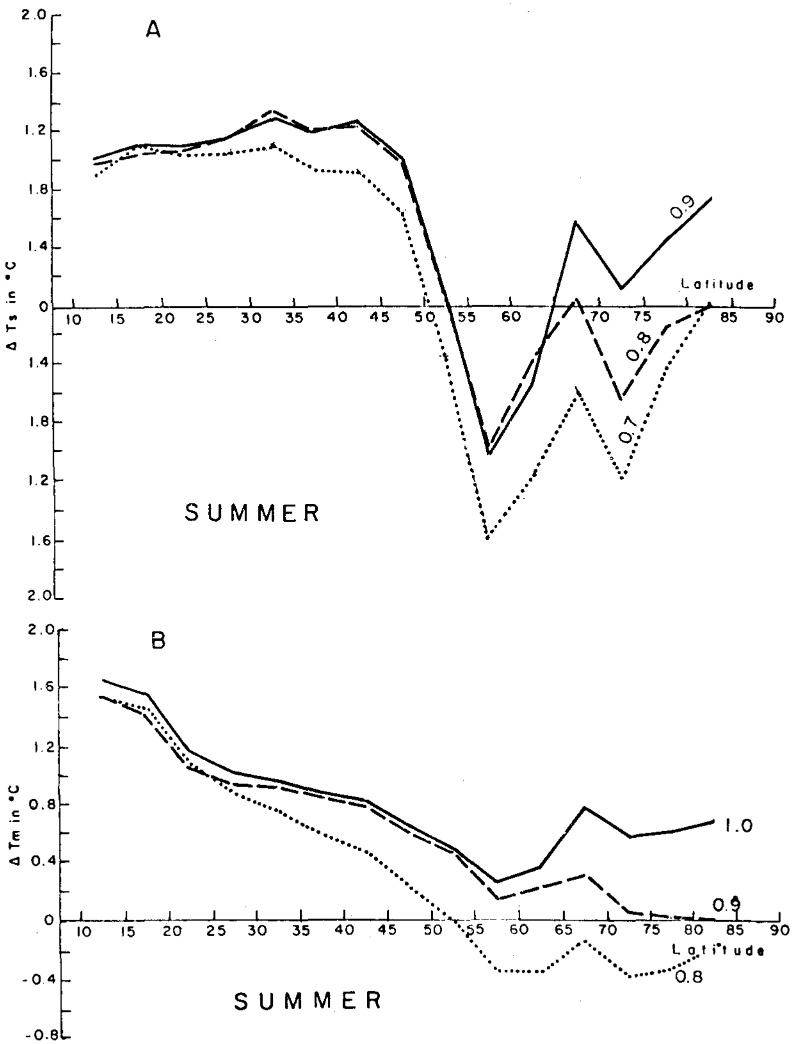

Fig. 12. Summer zonally averaged anomalies of the ground temperature (A) and the mean tropospheric temperatures (B), computed with a model that has annual cycle and variable cryosphere: The dotted line is the case when an ocean mixed layer is included, and the continuous line, the case when present ocean temperatures are prescribed. The dashed line is the case without annual cycle, and with a fixed cryosphere and prescribed present ocean temperatures.

comparisons of the surface temperature (A) and mean tropospheric temperature (B) anomalies. The dashed lines correspond to the experiment by Adem *et al.* (1984). The dotted and continuous lines correspond to the computations of this paper using a model with a 60 m ocean mixed layer and prescribing present temperatures, respectively.

The solution of the model with a mixed layer and annual cycle is colder than the other two. The average summer value corresponding to each case is shown over each of the curves.

Kutzbach and Otto-Bliesner (1982) have made computations for 9 kyr BP, which can be compared with our results. They used a low resolution general circulation model and prescribed the ocean temperature as present values. They first ran an experiment, prescribing present snow-ice conditions during a fourteen months simulation. They found from this experiment that the surface temperature anomaly over the continents is equal to 1.2°C, −0.7°C and −0.3°C for summer, winter and annual averages respectively. Comparison of these values with the corresponding ones of our experiments shown in Table 1 (1.9°C, −2.1°C and −0.7°C)and in Table 2 (2.2°C, −1.6°C and −0.3°C), shows that we get a warmer summer and a colder winter in both cases, but the same annual average in the case when present ocean temperatures are prescribed.

Kutzbach and Otto Bliesner (1982) also carried out a sensitivity computation in which they repeated the summer portion of their experiment, including the residual North American ice sheet at 9 kyr BP. They found that the primary climatic impact of the ice sheet is restricted to the North American continent. At the ice sheet surface, the temperature for summer of 9 kyr BP computed by them is 15-20°C lower than at the corresponding land surface grid point with no ice sheet. As a consequence, the zonal-average land surface temperature difference is changed markedly in those places. Furthermore they found that over Eurasia, the pattern and order of magnitude of temperature changes is the same as in the no-ice case. These results are confirmed by our experiments for 10 kyr BP, as follows from a comparison of Fig. 10B with Fig. 4C and from Fig. 11.

FINAL REMARKS AND CONCLUSIONS

In conclusion it can be stated that the insolation anomaly due to the orbital variations was the main factor that produced the departures of the climate of 10 kyr BP from the present climate. However, the existing ice sheets also affected in an important way the climate in higher and middle latitudes, especially in North America.

The computed climate of 10,000 years ago is warmer than present in summer and colder during the rest of the year. However, the surface ocean temperature anomaly remains below the present values during the whole year with an average value of −0.8 in winter, and −0.2 in summer and −0.5^{o}C for the whole year.

The results depend on the surface interactions associated with the anomalies in ocean temperature and on the boundary of snow and ice, as well as on the inter-seasonal interactions. Therefore, it is essential to include in the model the ocean mixed layer, the annual cycle and a variable cryosphere.

This series of experiments should not be considered as a definitive paleoclimatic simulation but primary as a test of model sensitivity to orbital parameters variations, and existing ice sheets at 10 kyr BP.

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