GLOBAL MODELLING OF CLIMATE AND ICE SHEETS

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1. THE USE OF ENERGY BALANCE MODELS FOR ICE AND CLIMATE STUDIES

For studies of long term global changes of climate, and ice cover, computationally efficient models are needed, which have a complete annual cycle, to compute temperatures over land and over ocean and to determine the seasonal distribution of sea ice and snow on the ground. Atmospheric general circulation models (GCMs), with coupled oceans, for prognostic sea surface temperatures (SSTs) require too much computer time to be used for large numbers of continuous simulations through ice age cycles to study the sensitivity to the numerous parameters required. The GCMs however can be used for series of "snapshot" climate simulations through the time series, e.g. Prell and Kutzbach [1].

The aim of the present work is to develop an effective Energy Balance Model (EBM) to simulate the global climate changes through the ice ages including the growth and decay of the large ice sheets. The time scales for the dominant physical processes in the ice sheet model and the EBM are sufficiently distinct that they can be largely decoupled. To study long term changes the EBM can be run for a series of "instants" with a prescribed ice sheet and other external factors held constant over a number of years (e.g. 80a) to reach an equilibrium climate. The ice sheet model can be run for a period (e.g. 1000a) with that prescribed climate before incremental changes such as the earth's orbital radiation regime are changed and a new sequence started.

Because of this effective decoupling of the ice sheet and climate time scales it is possible to study the independent effects on the global climate of the various slowly changing features such as the orbital radiation changes, and the ice sheet cover, by use of the EBM.

The purpose of this paper is firstly to demonstrate the use of the EBM to study the relative impacts of the various orbital parameter changes, independently, and in combinations, on the global climate. Secondly the EBM is used to assess the impact of changes in the northern hemisphere ice sheet cover on global climate. Thirdly simulations are carried out to model the seasonal global climate changes through the last ice age cycle, from 160,000a BP (years Before Present) to the present. A series of simulations have been carried out to show separately the effects of varying the orbital regime alone, without ice sheets growing, and then with the ice sheet changes included. The results provide some useful insight into the causes of the similarities and differences in the time series of historical climate changes at different locations around the globe.

2. OUTLINE OF THE MODEL

Only a brief description will be given here to indicate the salient features of the model. A full description of the model and its performance and sensitivities in simulating the earth's present climate are covered in detail by Rayner (unpublished [2]). The basic principles of global EBMs, have been described by many workers, e.g. North et al. [3]. The more important specific features of the model used here are as follows.

Two versions of the model have been developed: one with both a longitudinal and latitudinal specification of the global land and sea distribution, the other specifies only the total land and sea areas in each latitude band. The former has a much higher computational requirement so the present paper concentrates on the features and application of the latter. The latitudinal resolution used in these simulations is 1 degree. The atmospheric east-west heat transfer between land and ocean is parameterised as dependent on the surface temperature differences. The north-south atmosphere and ocean heat transports are similarly parameterised based on the north-south surface temperature distribution.

The radiation outside the earth's atmosphere is specified and takes account of the earth's orbital geometry from Berger [4]. Cloud amount and albedo is prescribed based on present day observed values, e.g. London [5], Warren et al. [6, 7].

Surface energy balance calculations are carried out separately over land and over sea to determine the surface temperatures. Precipitation is prescribed based on the present day distribution. Snow on the ground and sea ice thickness are computed through the year.

Effective ocean mixed layer depths are prescribed as a function of location and time of year based on the present distribution of ocean temperatures as given by Levitus [8]. These prescribed depths are used to compute the ocean storage and the sea surface temperatures from the surface energy balance.

Because the melting and freezing of snow and ice are related to a threshold temperature, mean diurnal cycles have also been parameterised. Surface temperature inversions, which are strong over snow and ice have also been parameterised based on present observed mean values as a function of temperature. A novel feature of the model is the inclusion of a spectrum of land surface elevations within each band to allow better representation of the areas covered by snow. The variation of temperature with elevation is determined from prescribed lapse-rates.

Although the model contains many features which are prescribed from the present climate, and which could well vary with climatic change, they are kept constant in the present study, to allow clearer assessment of the direct sensitivity of the surface temperatures, and the snow/ice lines, to the prescribed forcing.

The model gives a reasonably close fit to the observed annual cycle of mean surface temperatures over land and over ocean as a function of latitude, as well as the annual variation of the mean snowline on land and the extent of the sea ice. These results are detailed in Rayner (unpublished [2]) and will be described elsewhere. For the present we concentrate on the model's response to prescribed external forcing, with and without internal snow and ice feedback.

3. SENSITIVITY STUDIES

The response of the model to a wide range of sensitivity studies has been examined and is described in detail by Rayner (unpublished [2]). These include the responses to changes in cloud amount, cloud albedo, surface albedos, atmosphere and ocean transports, ocean flux under the sea ice, and changes in the snow albedo as a function of snow depth.

These sensitivity experiments were carried out as part of the process of studying the present climate and in obtaining a reasonable simulation of the present climate with the model using the best known values of the various parameters within the range of uncertainty. Here we consider the response of the model to the external forcing of changes to the solar constant. A series of studies have been carried out to examine the model response to increasing and decreasing increments in the solar constant with and without the snow and ice feedback. For the case of no feedback the seasonal snow and ice distribution is kept fixed at the present values.

The results for the 2% increase and 2% decrease in the solar constant are shown in Table 1. The snow and ice feedback is shown to be very strong, approximately doubling the direct effect of the radiation changes. The differences between the changes over land and sea, between seasons, and between latitudes are all relatively small. This contrasts greatly with the responses to the orbital changes where the ocean storage acts as a buffer. Some nonlinearity is apparent with the response to the solar decrease being larger than that for the corresponding increase.

TABLE 1

Model Response to Changes in Solar Constant(S)

	Northern Hemisphere			Southern Hemisphere			Global		
	Land	Sea	Zonal	Land	Sea	Zonal	Land	Sea	Zonal
A. Temperature decrease (°C) for 2% decrease of S.									
Jan.	4.9	5.1	5.0	4.5	4.1	4.2	4.8	4.5	4.6
July	4.0	4.1	4.0	5.0	5.0	4.9	4.2	4.6	4.5
Annual	4.4	4.7	4.6	4.7	4.4	4.5	4.4	4.6	4.5
B. Temperature decrease (°C) for 2% decrease of S with Snow and Ice fixed.									
Jan.	2.0	2.5	2.4	2.6	2.5	2.6	2.2	2.5	2.5
July	2.6	2.4	2.5	2.7	2.5	2.7	2.6	2.5	2.6
Annual	2.4	2.5	2.6	2.7	2.5	2.7	2.5	2.5	2.6
C. Temperature increase (°C) for 2% increase of S.									
Jan.	4.0	4.5	4.3	4.0	3.7	3.7	4.0	4.0	4.1
July	3.7	3.7	3.7	4.4	3.9	4.0	3.9	3.8	3.8
Annual	3.9	3.9	4.0	4.3	3.8	3.9	3.9	3.9	3.9

4. RESPONSES TO ORBITAL FORCING

A number of previous studies have been made to assess the earth's response to orbital forcing using EBMs e.g. Suarez and Held [9], [10], Schneider and Thompson [11]. One of the problems has been to find changes which are sufficiently large to cause the growth and retreat of the northern hemisphere ice sheets.

It was indicated by Budd and Smith [13], [14] that the crucial conditions for the onset of ice sheet growth was low northern summer temperatures at high latitudes (60°-70°N) over land. The results of the present model are therefore shown for January and July over land as a function of latitude.

The orbital changes of most relevance for ice sheet changes have been described by Budd and Smith [13], [14]. Here we only consider the changes from the present regime to the extremes of the parameters: time of perihelion (p, from 0 to 2π), the obliquity ($\phi°$) and the eccentricity (ε) which have occurred during the last ice age cycle. Table 2 shows the present values and the extreme values (since 125ka BP) which have been chosen for the simulation described below.

TABLE 2

Orbital Characteristics

		Present	Extreme during last 125ka
Perihelion			
(Shift from present)	p	0	π
Obliquity	ϕ	23.5°	22.1° and 24.5°
Eccentricity	ε	0.0167	0.0414

Results for the temperature deviations from the present for these extreme changes separately, are shown in Fig.1(a) to (d). Results for various extreme combinations are shown in Fig.1(e) to (g). The lowest temperatures in the northern high latitude summer occur with the combination: $p=0$, $\phi=22.1°$ and $\varepsilon=0.041$. These conditions would be most advantageous for ice sheet growth. The combination for highest northern high latitude temperatures is with $p=\pi$, $\phi=24.5°$ and $\varepsilon=0.041$, Fig.1(f). For the lowest summer temperatures in the south Fig.1(g) shows results for $p=\pi$, $\phi=22.1°$, $\varepsilon=0.041$. Although the extreme combinations did not occur exactly in phase during the period, at certain times they were approached quite closely.

Conditions for low temperatures at high northern latitudes in summer occured about 116ka BP. The results of Fig.1(e) show a July temperature drop of almost 4°C at about 65°N. It was found by Budd and Smith [13], [14] that such a summer temperature decrease would be sufficient to initiate the growth of a large ice sheet provided it was maintained for long enough. Similarly the high northern summer temperatures resulting from the combination shown in Fig.1(f) are relevant to the onset of the last interglacial and to a certain extent, but with a smaller eccentricity, for the last ice age retreat about 15ka BP. In Figs.1(e) to (g) sea surface temperatures are also shown which indicate that the modelled changes over land were in general much larger than those over the ocean.

5. RESPONSE TO ICE SHEET COVER CHANGES

At present the land area in the north, covered by ice represents a very small fraction of the total land area, in those latitude bands, and is primarily represented by the Greenland ice sheet. During the ice age the maximum extent of the ice sheet cover reached about 40°N in North America, but with an average latitude of the ice edge maximum over the land area of the hemisphere of 52°N. A number of studies have been made of the impact of the maximum ice age conditions on the climate using GCMs. Gates [15], Manabe and Hahn [16] and COHMAP members [17] prescribed the SSTs and sea ice, as well as the ice sheets. Manabe and Broccoli [18], [19], Broccoli and Manabe [20] computed SSTs with a mixed layer ocean over an annual cycle but did not include the meridional ocean transport. For the present model the ice sheet is prescribed, a combined atmosphere and ocean meridional transport is parameterised, and the temperatures and snow and ice lines over land and sea are computed through the annual cycle.

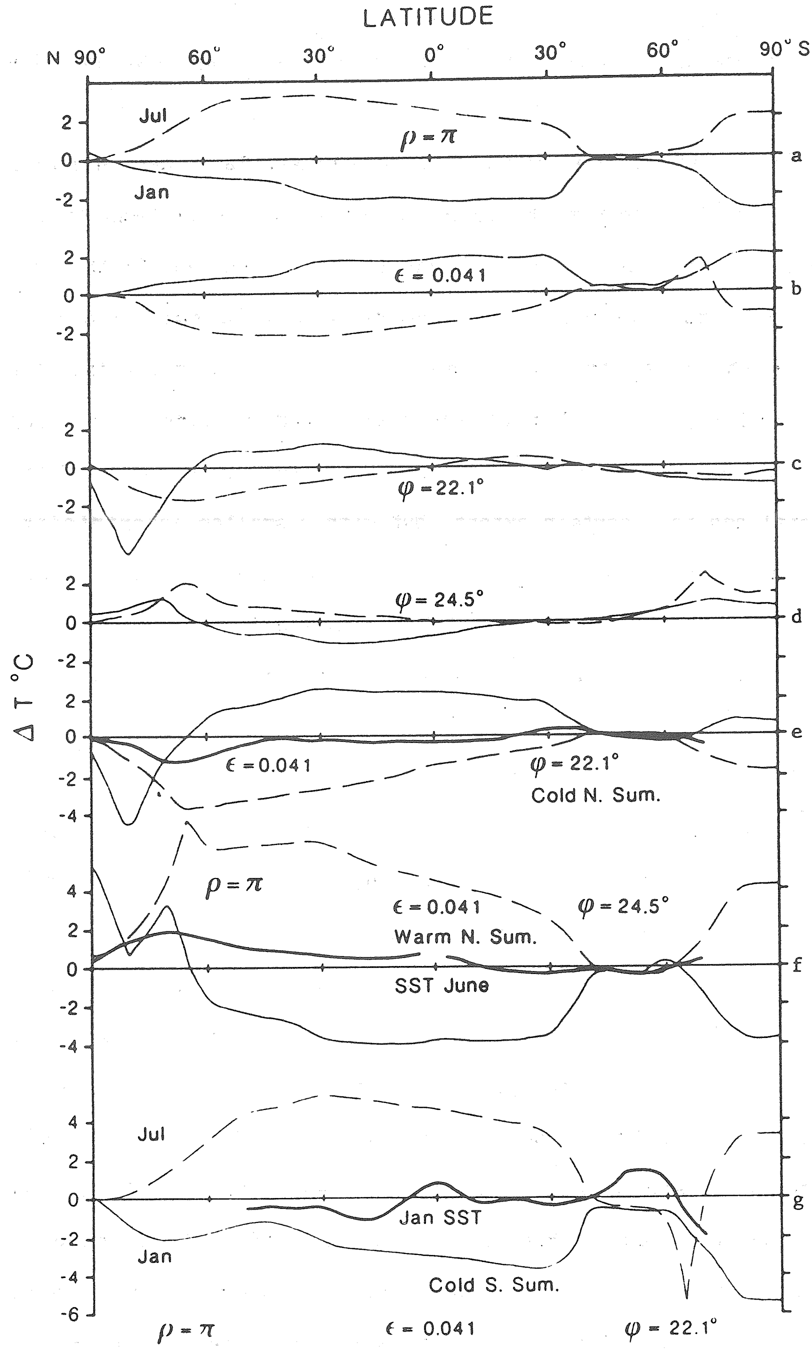

Fig. 1. The latitudinal and seasonal temperature response to orbital radiation changes is shown by the Rayner EBM model temperature changes over land in Jan. (full thin curves) and July (broken curves), for the following orbital changes (a) the perihelion shift by $p = \pi$, (b) the eccentricity increased to $\varepsilon = 0.041$, (c) the obliquity decreased to $\phi = 22.1^{o}$, (d) obliquity increased to $\phi = 24.5^{o}$, (e) a combination of $\varepsilon = 0.041$, and $\phi = 22.1^{o}$, (f) a combination of $p = \pi$, $\varepsilon = 0.041$, and $\phi = 24.5^{o}$, (g) a combination of $p = \pi$, $\varepsilon = 0.041$, and $\phi = 22.1^{o}$. The thicker curves indicate changes to the sea surface temperatures, in e, f and g.

Results for the July temperatures over land, and the annual mean zonal temperatures, as deviations from the present, are shown in Fig.2 (a) and (b). A series of simulations were carried out for mean land ice limits at different latitudes. The figures show results for ice limits varying from 70° to 45°N, spanning the mean ice age maximum extent of 52°N.

At present the winter snow cover over land reaches south of 50°N but then retreats to the Arctic ocean in summer. The main impact of the ice sheets then is to maintain the high surface albedos over land during the northern summer.

The results show similarity to those of Manabe and Broccoli [18], [19], with very large surface temperature changes over the ice sheets and with values of 5°-6°C in July over land for the ice age maximum, just south of the ice sheets, decreasing to about 4°C by the southern ocean, after which further amplification takes place from Antarctic sea ice expansion. An impact of 7°C is obtained for the annual mean change in the Antarctic near Vostok, which is large compared to effects due to the orbital changes. The changes over the ocean and for the annual mean are not as large as those over land for July, but they show a similar pattern and are not as reduced, relative to land seasonal changes, as for the orbital deviations.

It is clear from these results that the climatic feedback from the ice sheets, in regard to cooling, can be larger than the extreme effects of the orbital changes which occurred since 125ka BP.

6. TIME SERIES OF TEMPERATURE CHANGES THROUGH THE ICE AGE CYCLE

The model has been run for a series of simulations from 160ka BP to the present with the orbital radiation prescribed at 2,000 year intervals. In one case a series of equilibrium annual cycle climates were obtained without allowing the ice sheets to build up. This series gave the time series response to radiation forcing as shown for some selected latitudes in Fig.(3).

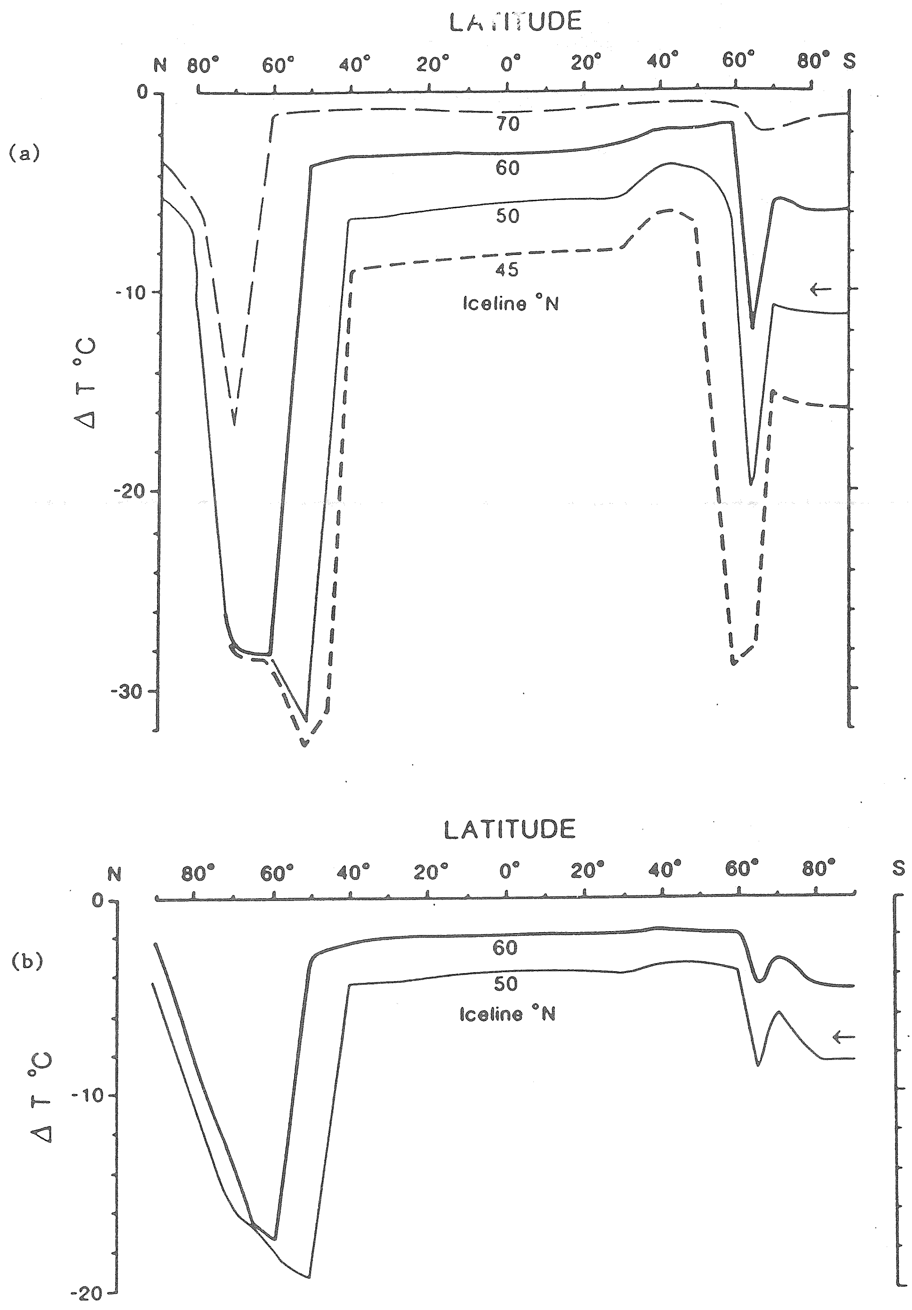

Fig. 2. The latitudinal response to the northern hemisphere ice sheet cover is shown by the EBM temperature changes (a) in July over land for the ice sheet on land reaching average latitudes of 70°N, 60°N, 50°N and 45°N, (b) the corresponding smaller annual zonal mean changes are shown for the ice sheet reaching average latitudes of 60°N and 50°N.
Note the large magnitude of the changes over the ice sheets then a decrease southward until amplification over the Antarctic sea ice and to a smaller extent over the Antarctic continent. The arrows indicate an expected response for the ice age maximum averaging 52°N from paleo data.

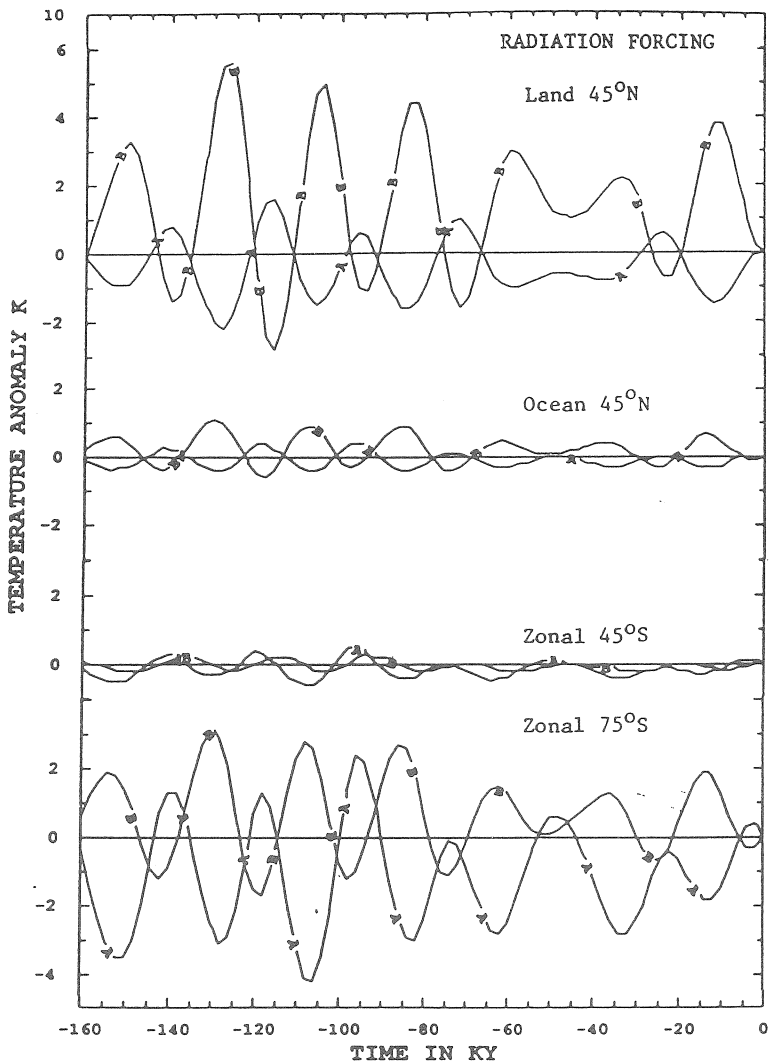

Fig. 3. Computed temperature changes from 160 ka BP to the present from radiation forcing only.
A: January, B: July.

In a second case the same series was computed including a prescribed northern hemisphere ice sheet cover. The prescription of the ice sheet cover was taken from the time series simulations of Budd and Smith [14], [21], for the North American ice cover, normalised to a mean hemispheric land ice cover maximum latitudinal extent based on the maximum extent about 18ka BP given by Denton and Hughes [22].

The results, for selected latitudes, of the temperature deviations from the present, for the combined forcing are shown in Fig.(4).

The radiation changes alone, give relatively large seasonal changes over land, but much smaller annual mean changes. Over the ocean the changes are very much smaller.

The combined forcing gives changes of the ocean which are largely dominated by the ice cover forcing. Over land the ice cover forcing dominates the annual changes with seasonal variations caused by the radiation changes.

The corresponding time series for the changes in the seasonal maximum and minimum of the northern hemisphere mean snow line over land and the Antarctic sea ice extent are shown in Fig.(5).

7. COMPARISON WITH OBSERVATIONS

The model results for the time series of surface temperature changes at different locations can be compared with a wide range of observations of proxy data for environmental change through the ice age cycle. For example, considerable similarity of patterns is found with a number of records with reasonable dating such as: sea sediments (Shackleton et al. [23], Sancetta et al. [24]), land sediments (Woillard and Mook [25], Adam and West [26]), sea level (Chappell [27], Edwards et al. [28]) and ice cores e.g. from Vostok (Jouzel et al. [29]).

The dominant effect of the northern hemisphere ice sheet cover on global climates, from the model results, gives good reason for the

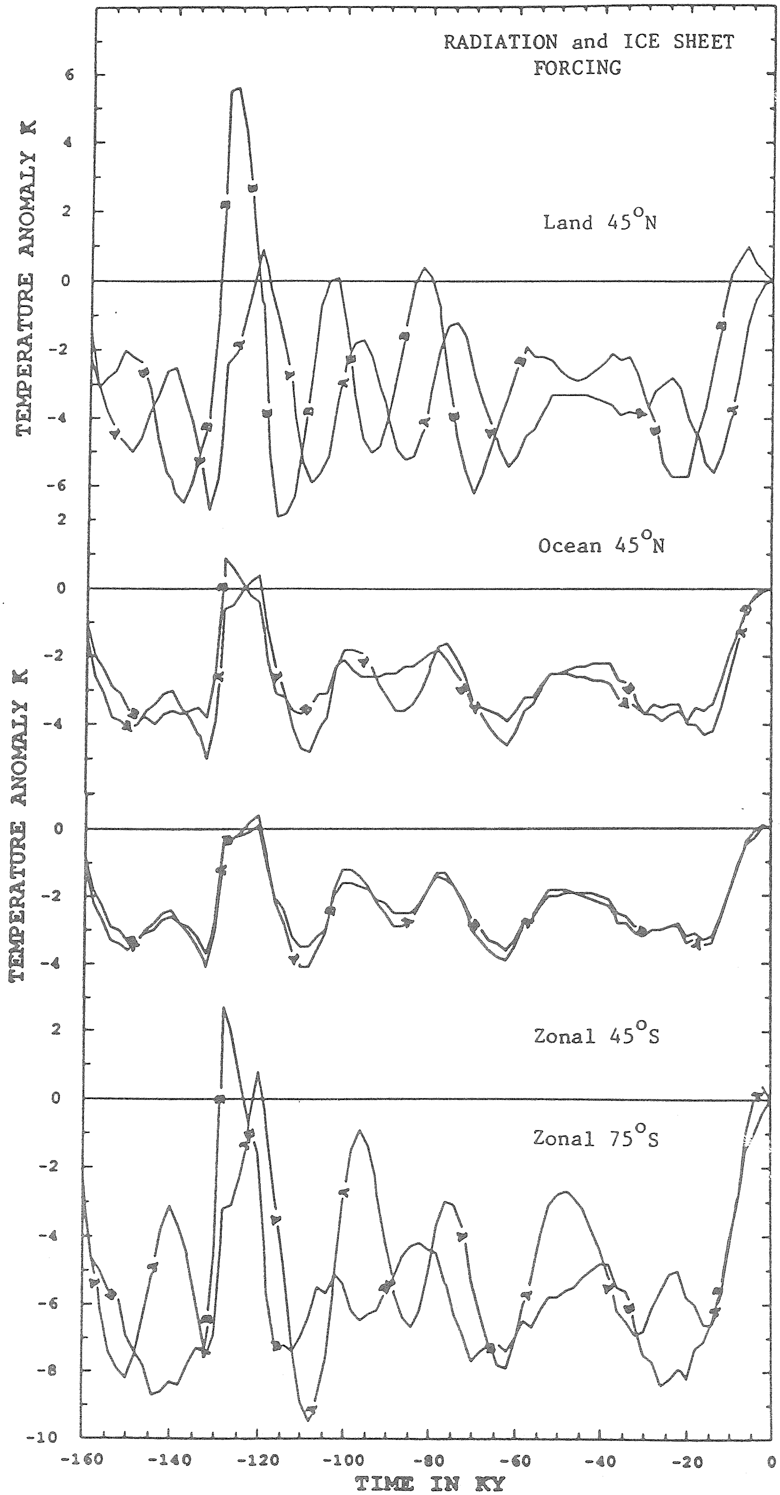

Fig. 4. Computed temperature changes from 160 ka BP from radiation and ice sheet forcing.
A: January, B: July.

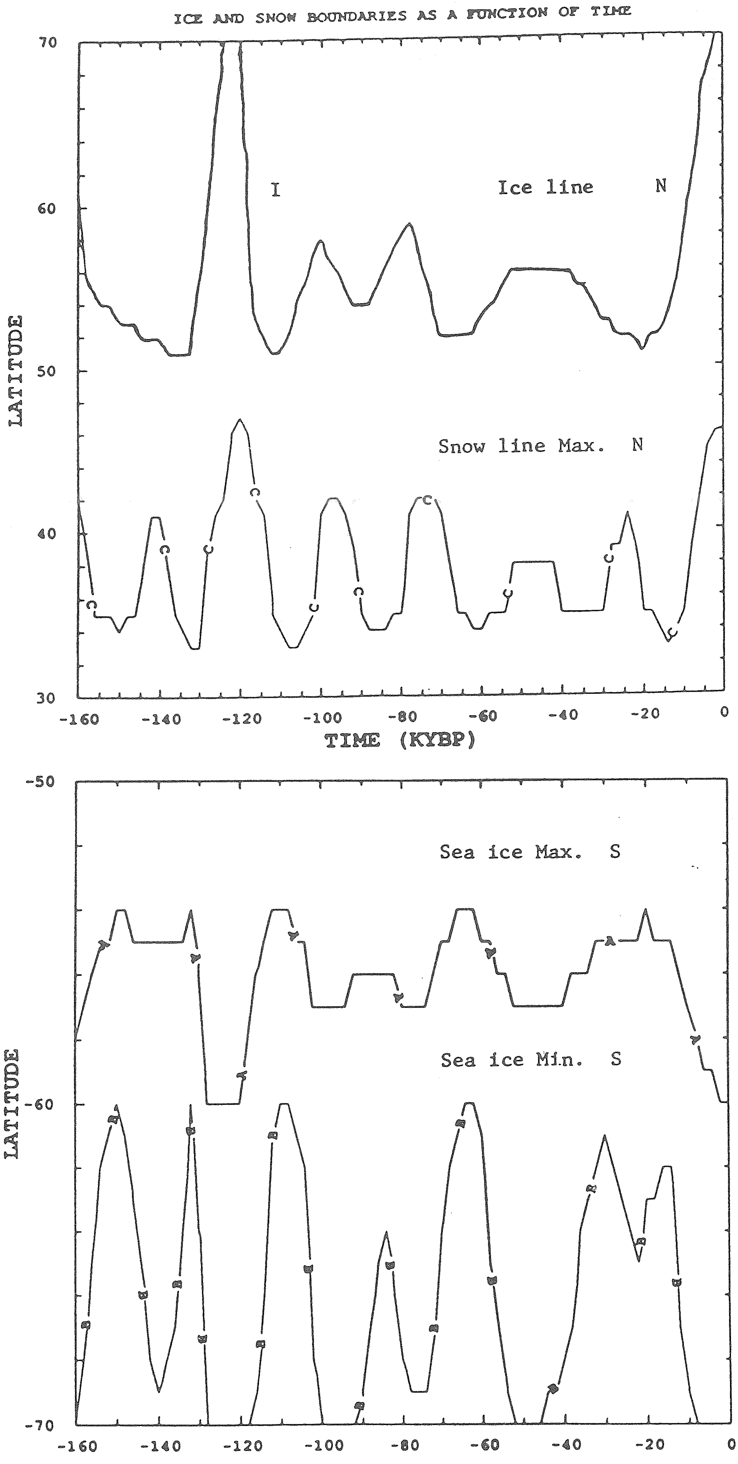

Fig. 5. Modelled snow and ice lines from 160 ka BP to present.
I: Average northern hemisphere ice sheet limit.
C: Average northern hemisphere snowline maximum.
A: Mean Antarctic sea ice maximum.
B: Mean Antarctic sea ice minimum.

apparently synchronous variations in the climate changes around the globe, when the long term summer radiation peaks in mid-latitudes of the hemispheres are out of phase. The model also shows how temperature changes over land (including ice sheets) can be much larger and more seasonal than the corresponding changes over the ocean.

The model results for 75°S have a marked similarity to the temperatures inferred from the Vostok isotope records: $\delta^{18}O$ by Lorius et al. [30] and δD, by Jouzel et al. [29].

It should be noted that the results presented in this paper are just the first of a series of studies with the model, taking account here, of only the radiation and ice sheet changes.

Other factors effecting surface temperatures which could be included in the model for sensitivity studies and in computing the time series include: carbon dioxide (from Barnola et al. [31]), particulates (cf. Harvey, [32]) and sea level changes (e.g. from Budd and Smith [14]; and Chappell [27]). In each case these effects could add to the ice age cooling.

Eventually it is proposed to make the EBM and the ice sheet models more fully coupled, to give a complete global coverage of interactive changes, including sea level, in the modelling of ice and climate changes through the ice age cycle.

REFERENCES

[1] PRELL, W.L. and KUTZBACH, J.E., (1987) Monsoon variability over the past 150,000 years. *J. Geophys. Res.* 92, No. D7, 8411-8425.

[2] RAYNER, P. 1989. Ph.D. thesis, Meteorology Department, University of Melbourne, (unpublished).

[3] NORTH, G.R., CAHALAN, R.F. and COAKLEY, J.A., (1981) Energy balance climate models. *Reviews of Geophys. and Space Phys.* 19, 91-121.

[4] BERGER, A., (1978) Long term variations of daily insolation and quaternary climatic variations. *J. Atmos. Sci.* 35, 2362-2367.

[5] LONDON, J., (1957) A study of the atmospheric heat balance. Report, Contract AF 19 (122)-165, College of Engineering, New York University, 99pp. (NTIS PB 115626).

[6] WARREN, S.G., HAHN, C.J., LONDON, J., CHERVIN, R.M. and JENNE, R.L., (1986) Global distribution of total cloud cover and cloud type amounts over land. NCAR Tech. Note NCAR/TN-273+STR, Nat. Cent. for Atmos. Res. Boulder, Colo.

[7] WARREN, S.G., HAHN, C.J., LONDON, J., CHERVIN, R.M. and JENNE, R.L., (1988) Global distribution of total cloud cover and cloud type amounts over the ocean. NCAR Tech. Note NCAR/TN-317+STR, Nat. Cent. for Atmos. Res. Boulder, Colo.

[8] LEVITUS, S., (1982) Climatological atlas of the world ocean. U.S.NOAA Professional Paper 13, Rockville, Md.

[9] SUAREZ, M.J. and HELD, I.M., (1976) Modelling climatic response to orbital parameter variations. *Nature,* 63, 46-47.

[10] SUAREZ, M.J. and HELD, I.M., (1979) The sensitivity of an energy balance climate model to variations in the orbital parameters. *J.Geophys.Res.* 84, No. C8, 4825-4836.

[11] SCHNEIDER, S.H. and THOMPSON, S.L., (1979) Ice ages and orbital variations some simple theory and modelling. *Quat. Res.* 12, 188-203.

[12] NORTH, G.R. and COAKLEY, J.A., (1979) Differences between seasonal and mean annual energy balance model calculations of climate and climate sensitivity. *J. Atmos. Sci.* 36, 1189-1203.

[13] BUDD, W.F. and SMITH, I.N., (1981) The growth and retreat of ice sheets in response to orbital radiation changes. In I.Allison, ed., Sea Level, Ice, and Climatic Change. International Association of Hydrological Sciences, Pub. No. 131, 369-409.

[14] BUDD, W.F. and SMITH, I.N., (1987) Conditions for growth and retreat of the Laurentide Ice Sheet. *Geograph. Phys. et Quat.* 41, No. 2, 279-290.

[15] GATES, W.L., (1976) The numerical simulation of ice-age climate with a general circulation model. *J. Atmos. Sci.* 33, 1844-1873.

[16] MANABE, S. and HAHN, D.G., (1977) Simulation of the tropical climate of an Ice Age. *J. Geophys. Res.* 82, No. 27, 3889-3911.

[17] COHMAP members,, (1988) Climatic changes of the last 18,000 years: observations and model simulations. *Science,* 241, 1043-1052.

[18] MANABE, S. and BROCCOLI, A.J., (1985) The influence of continental ice sheets on the climate of an ice age. *J. Geophys. Res.* 90, 2126-2190.

[19] MANABE, S. and BROCCOLI, A.J., (1985) A comparison of climate model sensitivity with data from the last Glacial Maximum. *J. Atmos. Sci.* 42, No. 23, 2643-2651.

[20] BROCCOLI, A.J. and MANABE, S., (1987) The effects of the Laurentide ice sheet on North American climate during the last glacial maximum. *Geograph. Phys. et Quat.* XLI, No. 2, 291-299.

[21] BUDD, W.F. and SMITH, I.N., (1985) A 500,000 year simulation of the North American ice sheet and climate. In Aust. Glaciol. Res. 1982-3. ANARE Research Notes 28, Antarctic Division, Hobart, 146-152.

[22] DENTON, G.H. and HUGHES, T.J. (eds.), (1981) The Last Great Ice Sheets, Wiley. New York, 484p.

[23] SHACKLETON, N.J., HALL, M.A., LINE, J. and SHUXI, C., (1983) Carbon isotope data in core V13-confirm reduced carbon dioxide concentration in the ice age atmosphere. *Nature*, 306, 319-322.

[24] SANCETTA, C., IMBRIE, J. and KIPP, N.G., (1973) Climatic record of the past 130,000 years in North Atlantic deep-sea core V23-82: Correlation with the terrestrial record. *Quat. Res.* 3, 110-116.

[25] WOILLARD, G.M. and MOOK, W.G., (1982) Carbon-14 dates at Grande Pile: Correlation of land and sea chronologies. *Science*, 215, 159-161.

[26] ADAM, D.P. and WEST, G.J., (1983) Temperature and precipitation estimates through the last glacial cycle from Clear Lake, California, Pollen Data. *Science*, 219, 168-170.

[27] CHAPPELL, J., (1983) A revised sea-level record for the last 300,000 years from Papua New Guinea. *Search*, 14, No. 3-4, 99-101.

[28] EDWARDS, R.L., CHEN, J.H., KU, T. -L., and WASSENBURG, G.J., (1987) Precise timing of the last Interglacial period from mass spectrometer determination of Thorium-230 in corals. *Science*, 236, 1547-1553.

[29] JOUZEL, J., LORIUS, C., PETIT, J.R., GENTHON, C., BARKOV, N.I., KOTLYAKOV, V.M. and PETROV, V.M., (1987) Vostok ice core: a continuous isotope temperature record over the last glacial cycle (160,000 years). *Nature*, 329, 403-408.

[30] LORIUS, C., JOUZEL, J., RITZ, C., MERLIVAT, L., BARKOV, N.I., KOROTKEVICH, Y.S. and KOTLYAKOV, V.M., (1985) A 150,000 year climatic record from Antarctic ice. *Nature*, 316, 591-596.

[31] BARNOLA, J.M., RAYNAUD, D., KOROTKEVICH, Y.S., LORIUS, C., (1987) Vostok ice core provides 160,000 year record of atmospheric CO_2. *Nature*, 329: 408-414.

[32] HARVEY, L.D.D., (1988) Climatic impact of ice-age aerosols. *Nature*, 334, 333-335.

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