Annals of Glaciology 14 1990

MODELLING GLOBAL ICE AND CLIMATE CHANGES THROUGH THE ICE AGES

by

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ABSTRACT

A global energy balance model has been developed which includes an interactive mixed layer ocean, sea ice, and snow and ice cover on the land. A full annual cycle is included and the model provides a close simulation to the variation of surface temperature through the year over land and over ocean as a function of latitude. The present annual variations of sea ice and snow on the ground are also well simulated. The model has been used for a wide range of sensitivity tests which include variations of the solar constant, surface albedos, and the effects of feed-back, or absence of feed-back, in the reponse of the snow and ice cover.

Studies have been made of the model's response to the long term variations in the Earth's orbital characteristics such as changes in the perihelion, the obliquity and the eccentricity as well as various combined changes. Independent sensitivity studies of the response of the model to the presence of the large ice sheets in the northern hemisphere have also been carried out. A series of model runs have been performed to study climatic changes around the globe from 160 000 years B.P. (Before Present) to the present. An examination is made of the impacts of the orbital changes alone, as well as with the feed-back from the large ice sheets.

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 effectively for series of "snapshot" climate simulations through the time series, e.g. Prell and Kutzbach (1987).

The purpose of this paper is first to demonstrate the use of an Energy Balance Model (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 160 000 a B.P. 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.

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 (1989, 1990) and Budd and Rayner (1989). The basic principles of global EBMs have been described by many workers, e.g. North and others (1981). The more important specific features of the model used here are as follows.

The model specifies only the total land and sea areas in each latitude band. The latitudinal resolution used in these simulations is 1°. 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 taking account of the Earth's orbital geometry from Berger (1978). Cloud amount and albedo is prescribed based on present day observed monthly mean values.

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 (1982). 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.

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 (1990) 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 feed-back.

SENSITIVITY STUDIES

The response of the model to a wide range of

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https://doi.org/10.3189/S0260305500008193 Published online by Cambridge University Press

TABLE I. 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.									
January	4.9	5.1	5.0	4.5	4.1	4.1	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.									
January	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.									
January	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

sensitivity studies has been examined and is described in detail by Rayner (1989, 1990). 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.

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 feed-back. For the case of no feed-back 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 I. The snow and ice feed-back 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 non-linearity is apparent with the response to the solar decrease being larger than that for the corresponding increase.

RESPONSES TO ORBITAL FORCING

A number of previous studies have been made to assess the Earth's reponse to orbital forcing using EBMs, e.g. Suarez and Held (1976, 1979), Schneider and Thompson (1979). 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 (1981, 1987) that the crucial conditions for the onset of ice-sheet growth were 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 (1981, 1987). Here we consider only 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 II shows the present values and the extreme values (since 125 ka B.P.) which have been chosen for the simulation described below.

TABLE II. ORBITAL CHARACTERISTICS

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

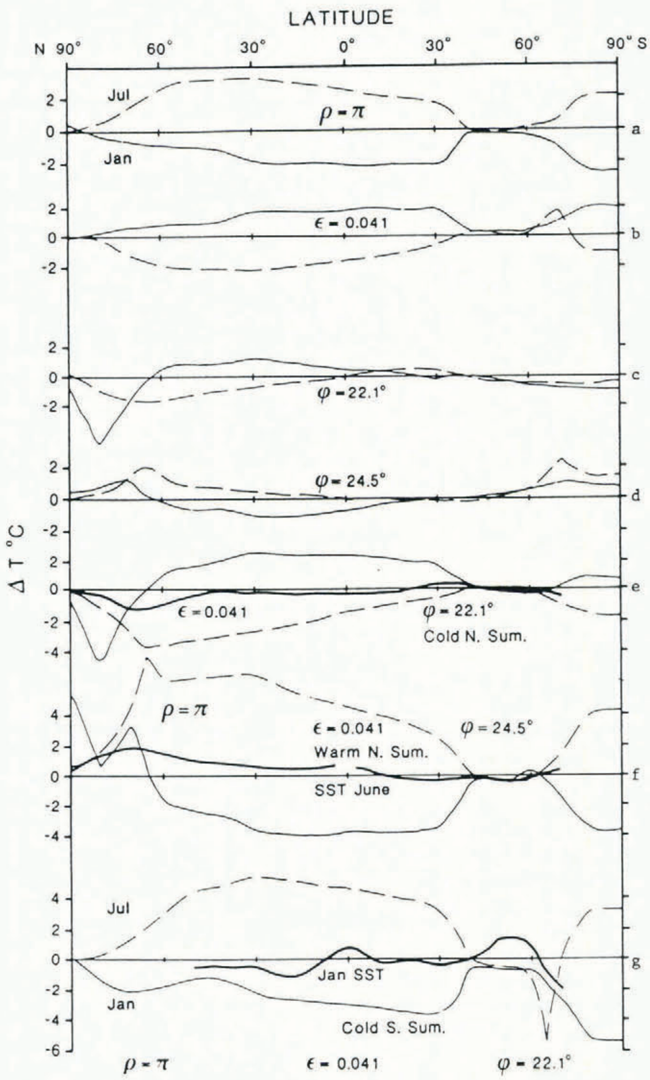

Fig. 1. Latitudinal and seasonal temperature response to orbital radiation changes shown by the Rayner EBM model temperature changes over land in January (full thin curves) and July (broken curves), for the following orbital changes: (a) the perihelion shift by $p = \pi$; (b) the eccentricity increased to $\varepsilon = 0.041$; (c) the obliquity decreased to $\phi = 22.1°$; (d) obliquity increased to $\phi = 24.5°$; (e) a combination of $\varepsilon = 0.041$ and $\phi = 22.1°$; (f) a combination of $p = \pi$, $\varepsilon = 0.041$, and $\phi = 24.5°$; (g) a combination of $p = \pi$, $\varepsilon = 0.41$, and $\phi = 22.1°$. The thicker curves in e, f and g indicate changes to sea surface temperatures.

Results for the temperature deviations from the present for these extreme changes separately, are shown in Figure 1(a) to (d). Results for various extreme combinations are shown in Figure 1(e) to (g). The lowest temperatures in the northern high latitude summer occur with the combination: $p = 0$, $\phi = 22.1^\circ$ and $\varepsilon = 0.041$ (Fig. 1(e)). These conditions would be most advantageous for ice-sheet growth. The combination for highest northern high latitude temperatures is with $p = \pi$, $\phi = 24.5^\circ$ and $\varepsilon = 0.041$ (Fig. 1(f). For the lowest summer temperatures in the south, Figure 1(g) shows results for $p = \pi$, $\varepsilon = 0.041$, $\phi = 22.1^\circ$. 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 occurred about 116 ka B.P. The results of Figure 1(e) show a July temperature drop of almost 4°C at about 65°N. It was found by Budd and Smith (1981, 1987) 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 Figure 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 15 ka B.P. In Figure 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.

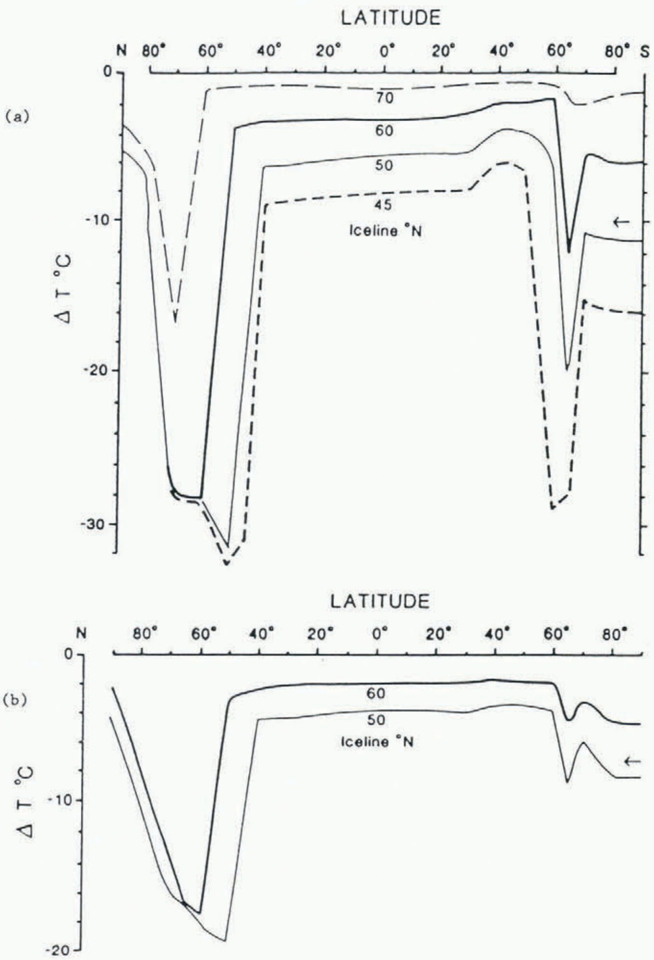

Fig. 2. Latitudinal response to the northern hemisphere ice sheet cover shown by the EBM temperature changes: (a) in July over land for the ice sheet on land reaching average latitudes of 70°N, 60°N, 50°N and 45°N; (b) the corresponding smaller annual zonal mean changes shown for the ice sheet reaching 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.

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.

Simulations were carried out for mean land ice limits at different latitudes. Results for the July temperatures over land, and the annual mean zonal temperatures, as deviations from the present, are shown in Figure 2(a) and (b). 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 of the EBM show similarity to those from the GCM simulations of Manabe and Broccoli (1985) 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 feed-back from the ice sheets, in regard to cooling, can be larger than the extreme effects of the orbital changes which occurred since 125 ka B.P.

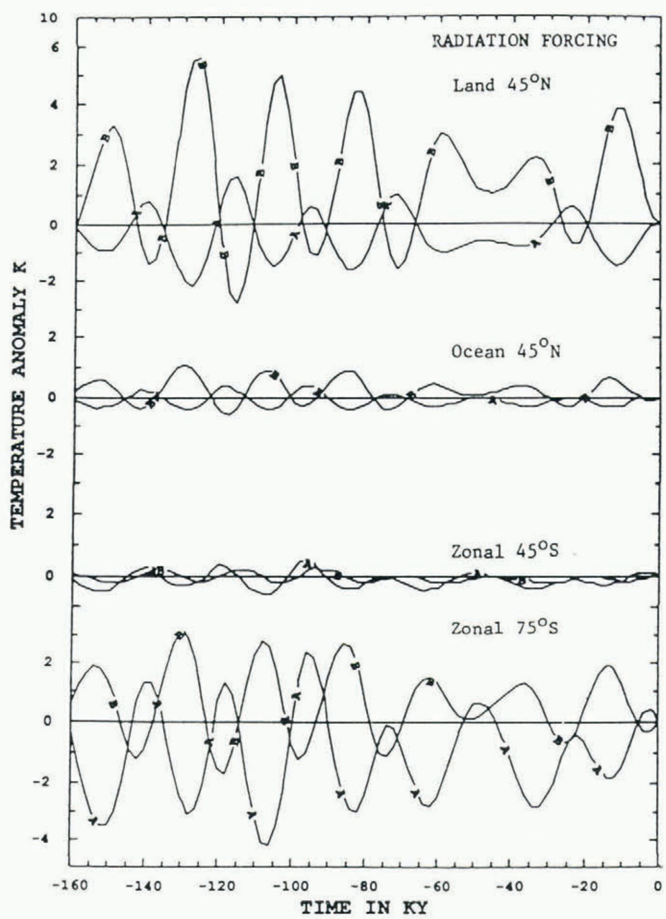

Fig. 3. Computed temperature changes from 160 ka B.P. to the present from radiation forcing only. —— January, --- July.

https://doi.org/10.3189/S0260305500008193 Published online by Cambridge University Press

TIME SERIES OF TEMPERATURE CHANGES THROUGH THE ICE AGE CYCLE

The model has been run for a series of simulations from 160 ka B.P. to the present with the orbital variation prescribed at 2000 year intervals. In one case a series of equilibrium annual cycle climates was obtained without allowing the ice sheets to build up. This series gave the time series response to radiation forcing alone as shown for some selected latitudes in Figure 3.

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 (1985 and 1987) for the North American ice cover, normalised to a mean hemispheric ice cover maximum latitudinal extent based on the maximum extent about 18 ka B.P. given by Denton and Hughes (1981).

The results, for selected latitudes, of the temperature deviations from the present, for the combined forcing are shown in Figure 4. The results of the radiation changes alone (Fig. 3) 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 (Fig. 4) 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 comparison of the results of Figures 3 and 4 show clearly the relative impacts of the radiation changes and the ice cover changes on the global climate as obtained by the EBM. The implications of these results in terms of seasonal and land–sea differences around the globe are discussed further in Budd and Rayner (1989).

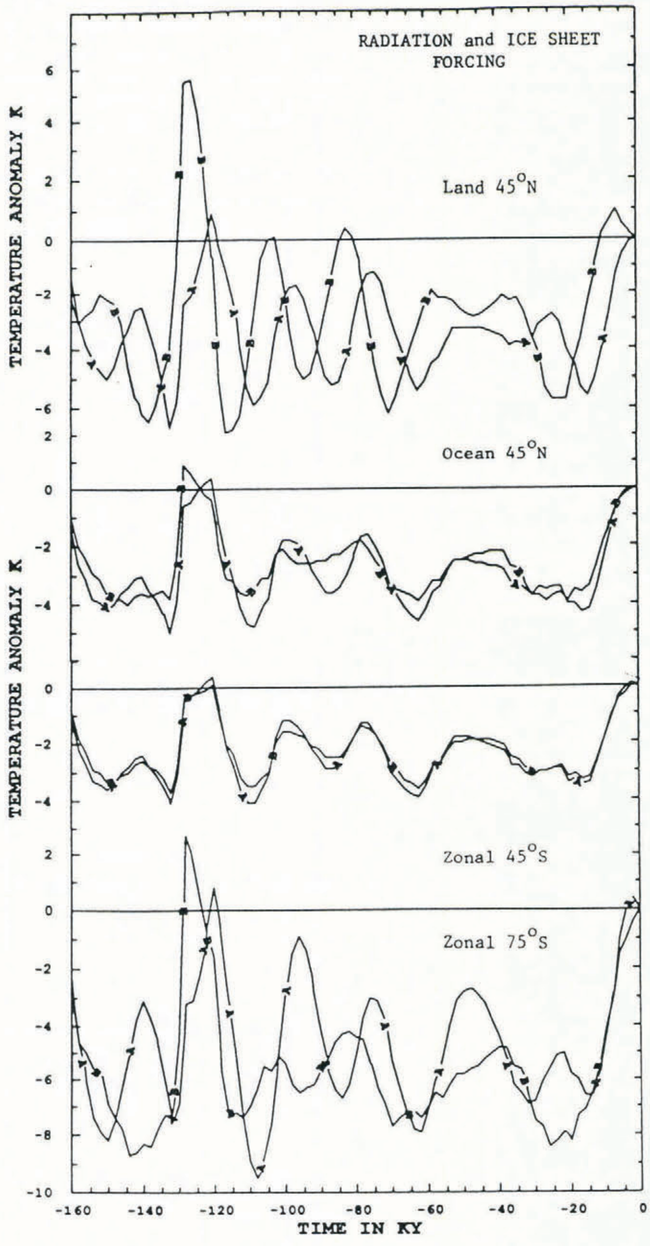

Fig. 4. Computed temperature changes from 160 ka B.P. from radiation and ice-sheet forcing. ——: January, ---: July.

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 are found with a number of records with reasonable dating such as: sea sediments (Sancetta and others, 1973; Shackleton and others, 1983), land sediments (Woillard and Mook, 1982), sea level (Chappell, 1983; Edwards and others, 1987) and ice cores e.g. from Vostok (Jouzel and others, 1987).

The dominant effect of the northern hemisphere ice-sheet cover on global climates, from the model results, gives good reason for the apparently synchronous variations in the climate changes around the globe, in spite of the long term summer radiation peaks in mid-latitudes of the hemispheres being 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 (particularly for July) have a marked similarity to the temperatures inferred from the Vostok isotope records: $\delta^{18}O$ by Lorius and others (1985) and δD by Jouzel and others (1987).

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 affecting surface temperatures which could be included in the model for sensitivity studies and in computing the time series include: carbon dioxide (from Barnola and others, 1987), particulates (cf. Harvey, 1988) and sea level changes (e.g. from Chappell, 1983; Budd and Smith, 1987). 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.

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