ON THE ORIGIN OF THE ICE AGES

J. Oerlemans

Institute of Meteorology and Oceanography, University of Utrecht, Utrecht, The Netherlands

ABSTRACT

Ice sheet dynamics provide a possible explanation for the 100 kyr power in climatic records. Some numerical experiments presented here show that even the transition from an essentially ice-free earth to a glacial cycle regime can be produced by a northern hemisphere ice-sheet model, provided that a slow general cooling on the northern hemisphere continents is imposed. Such a cooling could for example be the result of continental drift.

INTRODUCTION

Now that the Pleistocene glacial cycles have been documented quite well, e.g. Berger (1), more and more attention is paid to model simulation of the ice-volume record. Recent experiments (1,2,3,4) have shown that power on the 100 kyr time scale may be almost entirely due to ice-sheet dynamics. Here destabilization of an ice sheet by bedrock sinking and accumulation of heat plays an important role. Results from model experiments with both effects included were recently reported by the author (5).

Accepting that the regularity (on the 100 kyr time scale) of the ice ages is indeed mainly due to the physical properties of ice sheets, the question 'How did the Pleistocene start' can be considered. According to for instance Shackleton and Opdyke (6) and Hooghiemstra (7) the climatic evolution to the Pleistocene was rather discontinuous. The transition from an

A. L. Berger et al. (eds.), Milankovitch and Climate, Part 2, 607–611.

essentially ice-free climatic regime to one with regular glacial cycles occurred in a relatively short time. In this contribution some arguments will be given showing that such a rapid transition is in agreement with the explanation of glacial cycles from ice-sheet dynamics.

Results shown here were all obtained with the northern hemisphere ice-sheet model described in Oerlemans (5). Readers are referred to this article for a model description and general discussion.

BASIC IDEA

An ice sheet may form on the northern hemisphere continents when the snow line intersects the surface south of the polar sea, see Figure 1. Since the snow-line height will vary (due to, for instance, the Milankovitch insolation variations), the ice accumulation on the continent will be positive during a limited time. From model studies quoted above, we know that once an ice sheet has reached some size, it is able to continue its growth through the height-mass balance feedback, even when the snow line goes up again. So the probability that a large ice sheet can be established increases with the strength of the forcing (up and down movement of the snow line), as well as the mean elevation of the snow line.

As is immediately clear from Figure 1, a northward shift of the northern hemisphere continents is equivalent to a lowering of the (mean) snow line. Together with the fact that long-period internal oscillations may occur once the ice sheet has reached some critical size (5), it is obvious that a gradual northward shift of the northern hemisphere continents may lead to a rapid transition from an almost ice free northern hemisphere to a climate with glacial cycles. Precisely the same argument applies to every gradual global climatic cooling, whatever its cause may be.

From these considerations it is clear that, although the transition from one to another climatic regime may be well defined, the point in time at which the transition occurs is definitely not.

The transition is more likely to occur when variability of the snow-line elevation is large, and therefore a period with large eccentricity of the earth's orbit seems to be favourable.

However, movement of the snow line will have a substantial stochastic component, making the point(s) in time at which transition occurs practically unpredictable.

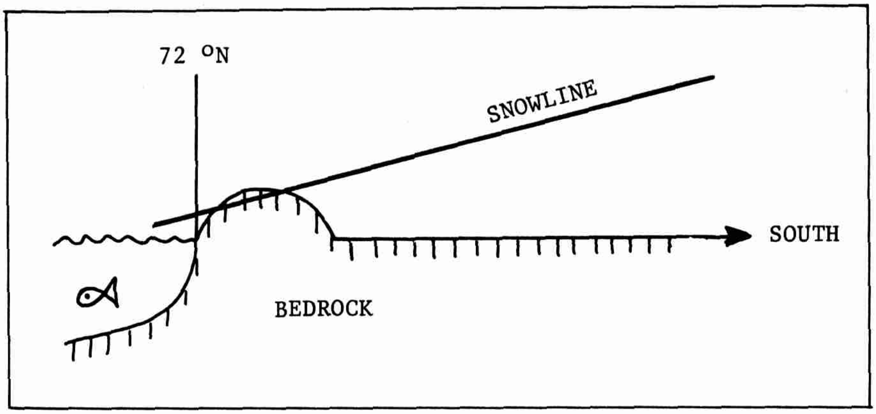

Figure 1 Northern hemisphere geometry for the ice-sheet model. The topographic bump is introduced to represent the plateaus that are actually found at high latitudes.

SOME MODEL CALCULATIONS

The ice-sheet model of which results will be discussed now is based on the geometry shown in Figure 1. It calculates ice flow along a meridian and includes a computation of the temperature field in the ice sheet, thus giving the possibility to take into account the effect of ice temperature and basal-water formation on the ice-mass discharge. The time-dependent reaction of the bedrock to ice loading is also calculated.

In Figure 2, two model runs are shown covering 1 million years of simulated time. In both runs the elevation of the snow line was prescribed to decrease steadily by 1 m per 5 kyr, while in the second run additional random forcing (white noise) was added. Model constants were chosen in such a way that transition occurs in the simulated range of time.

Run 1 shows very clearly how, at some critical value of the snow-line elevation, a self-sustained internal oscillation is set up. The oscillation is of the relaxation type : a gradual building-up of the ice sheet followed by a rapid decay (in accordance with the observational evidence). The small amount of ice present before the transition to the glacial cycle regime reflects some minor ice cover on the mountain (Fig. 1).

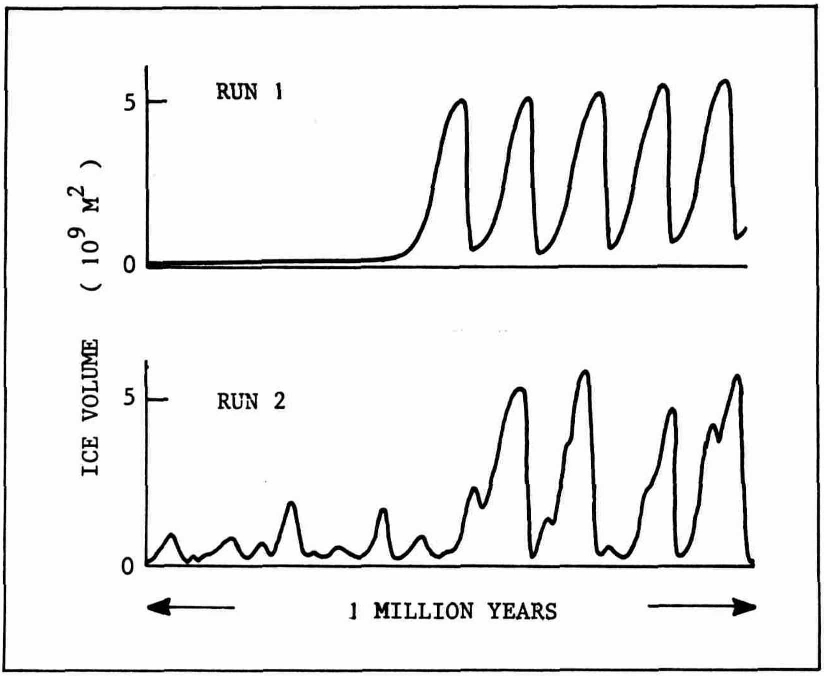

Figure 2 Two model runs of 1 million years of simulated time. The snow line elevation decreases steadily. In run 2 a random component is added to the movement of the snow line.

According to run 2, additional forcing on a smaller time scale makes the result look more realistic. Still a distinct change in the character of the solution occurs (for other "global" model constants), but the transition is smoothed somewhat by the presence of response in smaller time scales. Additional experiments confirmed that transition to a 100 kyr glacial cycle regime does not depend on the precise form of the forcing, as long as it does not have a strong component with a time scale close to or larger than the internal period of the ice sheet.

In conclusion, although the Milankovitch insolation variations may steer the Pleistocene glacial cycles, it appears that an ice-sheet model forced by random forcing of sufficient strength is capable of producing a transition from a comparatively ice-free to a glacial cycle climatic regime. A very slow, cooling of the global climate (associated with continental drift, for example) can easily cause such a transition.

REFERENCES

1. Berger, A. : 1981, Climatic Variations and Variability : Facts and Theories, 795pp., Reidel Publ. Company, Holland.
2. Oerlemans, J. : 1980, Nature 287, pp. 430-432.
3. Birchfield, G.E., Weertman, J., and Lunde, A.T. : 1981, Quaternary Research 15, pp. 126-142.
4. Pollard, D. : 1982, Nature 292, pp. 233-235.
5. Oerlemans, J. : 1982, Climatic Change 4, pp. 353-374.
6. Shackleton, N.J., and Opdyke, N.D. : 1976, Geol. Soc. Am. Mem. 145, pp. 449-464.
7. Hooghiemstra, H. : 1984, in : "Milankovitch and Climate", A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman (Eds), Reidel Publ. Company, Holland. This volume, p. 371.