NUMERICAL EXPERIMENTS ON ICE AGE CLIMATES*

JULIAN ADEM**
Centro de Ciencias de la Atmósfera y Facultad de Ciencias, Universidad Nacional Autónoma de México, México 20, D.F.

Abstract. Numerical experiments with a hemispheric thermodynamic model are carried out, using present and ice age conditions. The computed surface temperatures for 18,000 years ago are in good agreement with the CLIMAP values. It is shown that the snow-ice cap that existed in the summer 18,000 years ago created a feedback mechanism which was responsible for perpetuating these ice age conditions. The increase of insolation due to orbital variations was responsible, at least in part, for the shrinkage of the snow-ice cap from 18,000 to 8,000 years ago. It is shown that the effect on the earth-atmosphere system of the changes in insolation due to the orbital variations depends on the preexisting snow-ice cap. It is significant for the ice cap that existed 18,000 years ago and insignificant for present conditions. The numerical experiments suggest that the evolution of climate depends in an important way on the initial snow-ice conditions. Therefore, according to the model the problem of simulating the evolution of climate is not determined if one does not prescribe these snow-ice conditions.

1. Introduction

For more than a century, since Adhemar (1842) and Croll (1875) proposed an astronomical explanation for the ice ages, the problem of finding the reasons for explaining the appearance of an ice cap on the surface of the Earth and its advances and retreats through the years, has remained unsolved. Adhemar's judgement of the effects that would be produced by changes in the earth's orbit was erroneous (Woerkom, 1953), and Croll's hypothesis was not accepted on the basis of quantitative insufficiency. Köppen and Wegener (1924) proposed a theory according to which continental drift creates the initial setting for ice-ages while astronomical changes are only responsible for the repeated advances and retreats of the ice during each period of glaciation. To explain glacial interglacial cycles, Milankovitch (1920) computed the variations of the radiation received on a horizontal surface at the top of the atmosphere at selected latitudes, and correlated the variations with climate changes in the Pleistocene (Milankovitch, 1938, 1941). Simpson (1924) estimated that the temperature changes due to changes in insolation are of the order of only one or two degrees, which according to him are insignificant with respect to glaciations. Similar conclusions were also reached by Woerkom (1953), who nevertheless admitted that changes in the radiation caused by variations in the earth's orbit and its axis of rotation must have some effect on glaciations.

Recent numerical experiments carried out by Shaw and Donn (1968), Budyko (1969), Sellers (1970) and Saltzman and Verneker (1971) have confirmed Simpson's conclusions.

* Lamont Doherty Geological Observatory contribution No. 3115.
** Visiting Senior Research Associate at Lamont Doherty Geological Observatory, Columbia University.
More recently Suarez and Held (1976, 1979) reported numerical experiments in which they generate ice conditions and temperatures comparable to paleotemperatures. Several papers supporting the astronomical theory of climatic change, have appeared recently (Kukla, 1975; Weertman, 1976; Hays et al., 1976; Berger, 1977; Schneider and Thompson, 1979).

Regarding the continental drift as the initial cause of glaciations as proposed by Köppen and Wegener, Donn and Shaw (1975, 1977) have recently carried out numerical experiments that seem to support such a theory. Despite the fact that 18,000 years ago the radiation received by the earth was practically the same as that received today (see Figure 6 and discussion below), it is a well established fact that the last great ice age reached a maximum at that time (Flint, 1971). Quantitative estimates of sea-surface temperatures 18,000 years ago are available for the global ocean (CLIMAP Project Members, 1976). These estimates indicate that the ice-age ocean was generally several degrees colder than today. CLIMAP has also assembled data on the distribution and thickness of the continental ice sheets and major glacial systems as well as estimates of the corresponding albedo of both ice-covered and bare land surfaces.

Due to the availability of these data, it has been possible to carry out another type of numerical experiment in relation to the ice-ages. Gates, (1976a, b) using a global general circulation model, used the July-August data for surface conditions 18,000 years ago to compute the circulation and climate during the northern hemisphere summer at that time. He obtained results for July indicating that on a global basis the surface air temperature was 4.9°C lower than today’s, in general agreement with the available information obtained from pollen and periglacial evidence (Gates, 1976b). Similar experiments have been carried out by Williams et al. (1974) and Manabe and Hahn (1977), also using a global general circulation model, and by Alyea (1972), Newell and Herman (1975), and Saltzman and Vernekar (1975), using more simplified models.

In these numerical experiments the surface conditions play the role of fixed forcing functions. However, by keeping the surface conditions fixed, an inconsistency in the solution has been introduced. For example, given a certain ice-snow surface condition, the corresponding albedo used in a numerical model yields a set of climatic variables, but the surface temperature, together with precipitation and other variables computed in the model induce changes in snow-ice conditions with a corresponding surface albedo which is not necessarily equal to the initial one. Therefore, there must exist a mutual adjustment between surface albedo and some of the other climate variables that must be included in the model. This mutual adjustment was incorporated in a thermodynamic model (Adem, 1965a) in a crude way by coupling a surface temperature value with the snow-ice boundary, in such a way that any point with a surface temperature equal to or below such a value is defined as being covered by snow or ice, while temperatures above this value means absence of snow and ice. Other authors have also used empirical relations between albedo and surface temperature in Budyko-Sellers type models (Sellers, 1969; Gal-Chen and Schneider, 1975).

The purpose of this paper is to report numerical experiments using a thermodynamic model with this simple feedback mechanism, in order to investigate the effect on ice-age