Annals of Glaciology 3 1982

STUDIES OF THE ANTARCTIC AND PRESENT-DAY CONCEPTS OF GLOBAL GLACIATION

by

O. P. Chizhov and V. M. Kotlyakov

(Institute of Geography, Academy of Sciences of the U.S.S.R., Staromonetny per.29, Moscow 109017, U.S.S.R.)

ABSTRACT

Antarctic researches of the last decades have provided new facts which have made scientists change their ideas. The researches have shown a great difference between the history of the Antarctic and the northern hemisphere glaciation. The former is very old and stable, while the latter was ephemeral. An analogous one to the Antarctic ice sheet in the northern hemisphere is the Greenland inland ice. Both ice sheets are of continental-insular type; the Pleistocene ice sheets were of continental type proper. Ice-thickness measurements showed the topography of the bed under Antarctic ice and revealed a special type of ice sheet lying partly on the sea-floor: the West Antarctic continental-marine ice sheet. Such ice sheets could exist in the northern hemisphere too. They were especially unstable and their formation and destruction could serve as a triggering mechanism in alternating glacials and interglacials. The main concept is: all the great climatic variations during the Pleistocene were glacioclimatic ones where the feedback mechanism was the most important factor. But there are many details which are uncertain. The Antarctic and Greenland ice sheets are the key regions to research so that problems of glacioclimatology could be solved.

INTRODUCTION

Antarctic researches since 1956-57, when the IGY programme was put into being, have given many new facts which made scientists change their points of view long ago established. It has been considered that the origin of the Antarctic ice sheet was more or less synchronous to the Pleistocene ones in the northern hemisphere and was called forth by the same causes and mainly by some changes of global climate.

Antarctic researches show that the age of the Antarctic ice sheet is much older than any ice sheet in the northern hemisphere. The glaciers in Antarctic mountains appeared about 38 million years ago (Kennett 1977). For at least the last 10 million years the Antarctic ice sheet has existed and its size was always more or less the same as it is now (LeMasurier 1970, Rutford and others 1970, Hayes and others 1973, Kvasov and Verbitsky 1981). Antarctic climate was created by the ice and snow of the continent, and, more than that, the Antarctic ice sheet formation changed the climate not only of the southern hemisphere but also the whole globe as well (Budyko 1961, 1964, Avsyuk and Kotlyakov 1964, Shumskiy and others 1964). It is generally accepted now that all the large ice sheets change the climate around them. Snow and ice are products of climate, but when formed influence climate in return. There is some feedback mechanism (Voeikoff 1884). It seems trivial now, but many scientists worked for about a century to make such a concept generally accepted. The study of Antarctic glaciation and climate for the last 25 years brought an important contribution to this concept.

DEVELOPMENT OF IDEAS

The first man who set forth the idea of feedback mechanisms between snow and ice on the one hand and climate on the other was Voeikoff (1884); the second step was by Brooks (1926); and the first author who proposed the theory of glacioclimatic autofluctuations was Gernet (1930, see also Chizhov 1969, 1976). A theory very similar to his was quite independently published by Stokes (1955), and soon after him Ewing and Donn (1956, 1958) developed their version of the same idea. Since this time, the theory has become known and widely discussed and criticized in literature. The latter authors revised their work and published some other papers (Donn and Ewing 1966, 1968). But the Gernet-Stokes theory (which has to be called by the names of those who were the first to set it forth) explained the chain of events qualitatively; it was not confirmed by calculations or mathematical modelling, and in addition, there were some mistakes in it as it was proposed firstly by Gernet and later by Ewing and Donn. The main mistake they made was in the significance they ascribed to the Arctic Ocean, which, they postulated, was alternately free of ice and ice-covered, causing the glaciation and deglaciation of the surrounding continents. As it is known now after deep-sea cores from the Arctic Ocean were studied, the Arctic Ocean was not free of ice. It had been ice-covered for about 3 or 4 million years (Clark 1971). In Stokes' description, more generalized, the theory sounds better.

Recently, the autofluctuating nature of glacial-interglacial variations was confirmed by Sergin and Sergin (1978) and Sergin (1979) who carried out a study of the origins and thermodynamic mechanism of the large-scale glacial-interglacial variations by constructing a simplified thermodynamic model of the glaciers-ocean-atmosphere global system. They considered an aperiodic (non-fluctuating) regime in the southern hemisphere and a fluctuating one in the northern hemisphere. The period and amplitude of fluctuations in the model are of the same order of

https://doi.org/10.3189/S0260305500002512 Published online by Cambridge University Press

magnitude as those known from palaeoreconstructions.

The glacioclimatic history of the Antarctic makes us admit the theory described above, because any external cause, if it could explain fluctuations, would have acted in both hemispheres. But the Antarctic glaciation, after it had formed, was and is stable. It means that we must look for other internal causes that make glaciers fluctuate.

TYPES OF LARGE ICE SHEETS

There is a type of large ice sheet that we have now. It is the continental-insular type. There are two of them: the Antarctic and Greenland ice sheets. The areas they cover are measured in millions of square kilometres. Other ice caps are much less; their areas are not more than 20 to 30 000 square kilometres each. There are no ice caps of intermediate size existing now.

There is rather a good correlation between the area A and the thickness H of all ice caps and ice sheets (Fig.1). It can be expressed by an equation:

$$A = KH^4,$$

where K is a constant coefficient. The power of H is one that corresponds to the elliptical profile of the ice-cap surface (Chizhov 1976: 142-145, Khodakov 1978: 148-149). It is seen in Figure 1 that there is a gap between the two contemporary large ice sheets (Antarctic and Greenland) and the other lesser ice caps. But when Pleistocene ice sheets increased their sizes they passed through all the intermediate ones. This means that such sizes can exist only in the process of increasing and decreasing the large ice sheets.

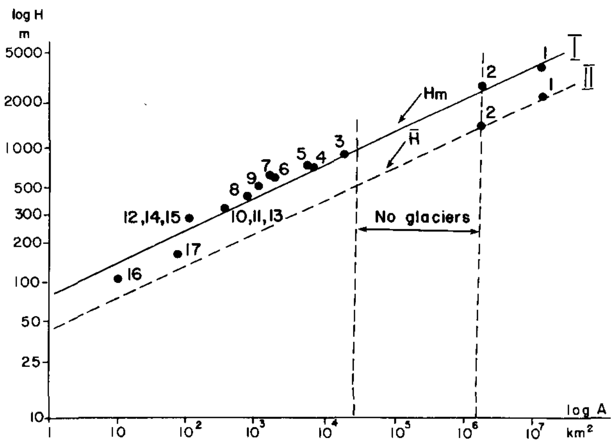

Fig.1. Area of ice caps and ice sheets A versus maximum height H_m of their surface (line I) or average thickness $\bar{H}$ of ice (line II) in logarithmic scale. 1: Antarctic; 2: Greenland; 3 to 16: other ice caps of lesser area.

The ice sheets of the continental-insular type are stable ones. The Antarctic ice sheet is not less than 10 million years old; the age of the Greenland ice sheet is about 2 to 4 million years. But the time of existence of the Pleistocene ice sheets (Scandinavian, Laurentide, and others) was something like 10 to 20 000 years; they were ephemeral. They were the ice sheets of the continental type proper. While the main mode of ablation of the continental-insular ice sheets is calving, the mode of ablation of these Pleistocene ice sheets was melting over the wide ablation zone along their southern margins. The first author who understood and explained the stability of the Antarctic ice sheet by its insular position was E S Gernet (1930).

There is, and was in the past, the third type of large ice sheet, such as the West Antarctic: the continental-marine type lying partly on the sea-floor. Ice sheets like this could exist in the northern hemisphere too (Mercer 1970). There is evidence that such an ice sheet was formed during the last glacial epoch over the Barents Sea continental shelf (Schytt and others 1968), and that the pan-Arctic ice sheet of the continental-marine type could cover other northern shelves and the central Arctic (Hughes and others 1977). Ice sheets of the continental-marine type were especially unstable, and their formation and destruction could be a triggering mechanism to advances and retreats during alternating glacials and interglacials. The origin and disappearance of continental -marine ice sheets can be connected with sea-ice formation, and many problems arise here (Olausson 1972, 1975, Zakharov 1978, 1980).

EXTERNAL INFLUENCES

The fluctuations of insolation because of changing elements of the Earth's orbit attract the most attention among the external causes influencing alternation of glacials and interglacials. Their significance has been proved (Hays and others 1976). But the fact is that, for the long pre-Pleistocene time, orbital influences were negligible and became noticeable only after the Pleistocene ice sheets of the continental type proper formed (Woldstedt 1958). The influence of variations in the Earth's orbit is weak but is increased by glaciation. Weertman (1976) has shown that Milankovitch insolation variations do work, but by means of ice spreading in glaciers. It is very important by itself because an ice sheet, after reaching some critical size, began to spread without any climatic change (Tronov 1951), Weertman 1961). Modelling by Sergin and Sergin (1978) has shown that Milankovitch insolation variations change the period and amplitude of glacial-interglacial fluctuations.

CONCLUSION

The history of Cenozoic glaciation as it is known owing to Antarctic studies together with the achievements of marine geology seems clear in general. And it is simpler in the Antarctic than in the Arctic.

Shifting of the Antarctic continent into its polar position, which took place in Mesozoic time, did not immediately result in its glaciation. Rather even and warm climates predominated over the globe. The first glaciers appeared in the Antarctic mountains only in the Tertiary period, about 38 million years ago (Eocene-Oligocene boundary). Their appearance was connected with general uplift of the land and increased precipitation, which was the consequence of departing of Australia from the Antarctic and forming the strait between them. The formation of Drake Strait later resulted in the circumpolar current of west winds round the Antarctic continent. This current isolated it and provided for precipitation which gave enough accumulation on glaciers. Glaciers grew in the mountains, joined together, descended onto the neighbouring plains, and reached the sea, producing icebergs. About 20 million years ago, the East Antarctic ice sheet formed, later the West Antarctic one, and by 5 million years ago, the Antarctic ice cover reached its maximum size, which was more than at present (Kennett 1977, Kvasov and Verbitzky 1981). At the same time, growing glaciation led to cooling of the air and the surrounding water owing to loss of heat from the melting of icebergs. Cooling waters sank down, where a cold deep layer was forming and spreading gradually towards the north up to the Equator and farther. The mass balance of the Antarctic ice sheet caused its quasistability. Ice margins calve when they reach the sea, balancing the accumulation of snow on the surface of the ice sheet. Spreading farther north is limited by the sea.

Global cooling led to the formation of glaciers in the northern hemisphere, first of all on the great near-polar island of Greenland, where the

https://doi.org/10.3189/S0260305500002512 Published online by Cambridge University Press

Atlantic current brought enough precipitation. Glacial and climatic history of Greenland is similar to that of Antarctica. Its glaciation was stimulated by the same causes and resulted in the same consequences as the glaciation of the Antarctic, i.e. further gradual cooling and ice formation over the neighbouring lands around the North Atlantic. Study of deep-sea sediments shows the appearance of sea ice in the Arctic Ocean about 3.5 million years ago (Clark 1971). At the same time the glaciers of Greenland could reach the sea. The age of the Greenland ice sheet is estimated as 3 million years or so. But the history of its glaciation is known less well than the history of Antarctica. The sequence of events in the Arctic does not seem as evident as in the Antarctic, where the first glacial event was the inception of glaciers in the Antarctic mountains. The sea ice could appear much later. But how did events go in the north polar area?

There are many discussions around the problem. Some authors think that the sea ice appeared first in the north polar area (Zakharov 1978, 1980), starting the chain of events known in the glacial history of the northern hemisphere. However, the appearance of sea ice in the deep central Arctic Basin before other glacial events is difficult to imagine (the salt water must be cooled below freezing point over its whole depth). It is evident that the freeze-up of sea-water could begin first near the mouths of great rivers where a surface layer of light fresh water could form. But all the same, one must agree that at the snow-line in the mountains, the temperature would descend lower and snow cover would form earlier than at sea level. Everything convinces us that, in the northern hemisphere, glaciation formed first in mountain regions and, what is most important, among mountains in Greenland where it began from small mountain glaciers and then spread over the island as a large ice sheet.

A special and difficult problem is the further evolution of glaciation in the northern hemisphere which is quite different from Antarctic glaciation. The glaciation was fluctuating and its fluctuations had very great amplitudes. They began, as it is generally accepted, about 700 000 years ago when ice sheets of continental type proper reached their maximum sizes. Their southern margins spread up to 40 or 50°N in the Atlantic part of the northern hemisphere. Their changes were of autofluctuating character, but their number is not known exactly, and the mechanism of fluctuation is understood only in general. Many details remain which are difficult to explain.

Researches in the Antarctic have given much to the understanding of glacioclimatic evolution. But a good deal of studies have to be done for better understanding. The Greenland ice sheet and the Arctic Ocean are the key regions of study for the glaciologist, besides the Antarctic.

REFERENCES

Avsyuk G A, Kotlyakov V M 1964 Diskussionnyye voprosy sovremennoy glatsiologii [Disputable questions of contemporary glaciology]. *Rezul'taty Issledovaniy po Programme Mezhdunarodnogo Geofizicheskogo Goda. Glyatsiologicheskiye Issledovaniya* Ser 9: 126-142

Brooks C E P 1926 *Climate through the ages; a study of the climatic factors and their variations.* London, Ernest Benn

Budyko M I 1961 O termicheskoy zonal'nosti Zemli [On the thermal zonality of the Earth]. *Meteorologiya i Gidrologiya* 11: 7-14

Budyko M I 1964 Teplovoy balans Zemli [Heat balance of the Earth]. *Geofizicheskiy Byulleten'* 14: 39-44

Chizhov O P 1969 On the hypothesis of ice ages suggested by Captain E.S. Gernet. *Journal of Glaciology* 8(53): 225-228

Chizhov O P 1976 *Oledeneniye Severnoy polyarnoy oblasti [Glaciation of the north polar area].* Moscow, Nauka (*Rezul'taty Issledovaniy po Mezhdunarodnym Geofizicheskim Proyektam (Unnumbered Series)*)

Clark D L 1971 Arctic Ocean ice cover and its late Cenozoic history. *Geological Society of America. Bulletin* 82(12): 3313-3323

Donn W L, Ewing M 1966 A theory of ice ages. III. *Science* 152(3720): 1706-1712

Donn W L, Ewing M 1968 The theory of an ice-free Arctic Ocean. *Meteorological Monographs* 8(30): 100-105

Ewing M, Donn W L 1956 A theory of ice ages. [I.] *Science* 123(3207): 1061-1066

Ewing M, Donn W L 1958 A theory of ice ages. II. *Science* 127(3307): 1159-1162

Gernet Ye S 1930 *Ledyanyye lishai, novaya lednikovaya teoriya, obshchedostupno izlozhennaya* [The ice lichens, a new theory of ice ages] Tokyo, E S Gernet

Hayes D E, Frakes L A and 10 others 1973 Leg 28 deep-sea drilling in the Southern Ocean. *Geotimes* 18(6): 19-24

Hays J D, Imbrie J, Shackleton N J 1976 Variations in the Earth's orbit: pacemaker of the ice ages. *Science* 194(4270): 1121-1132

Hughes T J, Denton G H, Grosswald M G 1977 Was there a late-Würm Arctic ice sheet? *Nature* 266 (5603): 596-602

Kennett J P 1977 Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography. *Journal of Geophysical Research* 82(27): 3843-3860

Khodakov V G 1978 *Vodno-ledovyy balans rayonov sovremennogo i drevnego oledeneniya SSSR [Water and ice balance of the areas of present and ancient glaciation of the USSR].* Moscow, Nauka (*Rezul'taty Issledovaniy po Mezhdunarodnym Geofizicheskim Proyektam (Unnumbered Series)*)

Kvasov D D, Verbitsky M Ya 1981 Causes of Antarctic glaciation in the Cenozoic. *Quaternary Research* 15(1): 1-17

LeMasurier W E 1972 Volcanic record of Cenozoic glacial history of Marie Byrd Land. *In* Adie R J (*ed*) *Antarctic geology and geophysics. Symposium, Oslo, 1970* Oslo, Universitetsforlaget: 251-259

Mercer J H 1970 A former ice sheet in the Arctic Ocean? *Palaeogeography, Palaeoclimatology, Palaeoecology* 8(1): 19-27

Olausson E 1972 Oceanographic aspects of the Pleistocene of the Arctic Ocean. *Inter-Nord* 12: 151-170

Olausson E 1975 On the course of a glacial age. *In Proceedings of the WMO/IAMAP symposium on long-term climatic fluctuations, Norwich, 1975.* Geneva, World Meteorological Organization: 47-52 (WMO 421)

Rutford R H, Craddock C, White C M, Armstrong R L 1972 Tertiary glaciation in the Jones Mountains. *In* Adie R J (*ed*) *Antarctic geology and geophysics. Symposium, Oslo, 1970.* Oslo, Universitetsforlaget: 239-243

Schytt V, Hoppe G, Blake W Jr, Grosswald M G 1968 The extent of the Würm glaciation in the European Arctic. A preliminary report about the Stockholm University Svalbard Expedition 1966. *International Association of Scientific Hydrology Publication* 79 (*General Assembly of Bern 1967 — Snow and Ice*): 207-216

Sergin V Ya 1979 Numerical modelling of the glaciers-ocean-atmosphere global system. *Journal of Geophysical Research* 84(C6): 3191-3204

Sergin V Ya, Sergin S Ya 1978 *Sistemnyy analiz problemy bol'shikh kolebaniy klimata i oledeneniya Zemli [System analysis of the problem of great fluctuations of climate and glaciation of the Earth].* Leningrad, Gidrometeoizdat

https://doi.org/10.3189/S0260305500002512 Published online by Cambridge University Press

Shumskiy P A, Krenke A N, Zotikov I A 1964 *Ice and its changes*. *In* Odishaw H (*ed*) *Research in geophysics Vol 2. Solid earth and interface phenomena*. Cambridge, MA, MIT Press: 425-460
Stokes W L 1955 Another look at the ice age. *Science* 122(3174): 815-821
Tronov M V 1951 Teoreticheskiye itogi lednikovykh issledovaniy na Altaye [Theoretical results of glacier studies in the Altay]. *Voprosy geografii Sibiri* 2: 3-68
Voeikoff A I 1884 *Klimaty Zemnogo shara, v osobennosti Rossii [Climates of the Globe, especially of Russia]*. Peterburg
Weertman J 1961 Stability of ice-age ice sheets. *Journal of Geophysical Research* 66(11): 3783-3792
Weertman J 1976 Milankovich solar radiation variations and ice age ice sheet sizes. *Nature* 261(5555): 17-20
Woldstedt P 1958 Eine neue Kurve der Würm-Eiszeit. *Eiszeitalter und Gegenwart* 9: 151-154
Zakharov V F 1978 *Mirovoy okean i lednikovyye epokhi pleystotsena [The world ocean and glacial epochs of the Pleistocene]*. Leningrad, Nauchno-Issledovatel'skiy Institut Arkticheskiyi Antarkticheskiy
Zakharov V F 1980 Polyarnyye l'dy: sledstviye ili prichina izmeneniya klimata? [Polar ice: effect or cause of climatic change?]. *Priroda* 2: 70-79

https://doi.org/10.3189/S0260305500002512 Published online by Cambridge University Press