Meded. Werkgr. Tert. Kwart. Geol. | vol. 11 nr. 2 | pp. 53-83 | juni 1974

POSSIBLE CAUSES OF GLACIATIONS

by

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Van den Heuvel, E. P. J. & P. Buurman. Possible causes of glaciations. - Meded. Werkgr. Tert. Kwart. Geol., 11 (2): 53 - 83, 8 figs., june 1974.

Evidence of glaciation in the Earth's history is briefly reviewed and possible cosmic and terrestrial causes of climatic change are discussed. The only plausible cause of large Ice Ages seems to be a combination of continental uplift, mountain building and thermal isolation of one or both of the poles, as suggested by Ewing & Donn. The large variation in mid-latitude glaciations during the Pleistocene, on a timescale of about 40.000 years, may have been triggered by insolation variations of the type calculated by Milankovitch.

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CONTENTS:

SAMENVATTING

Een kort overzicht wordt gegeven van de sporen van vergletscheringen uit verschillende perioden van de geschiedenis der aarde, en van de mogelijke kosmische en aardse oorzaken van klimaatsveranderingen. De jongtertiair-pleistocene vergletscheringen maken deel uit van één grote ijstijd, die ongeveer 7 miljoen jaar duurde en misschien nog niet afgelopen is. De duur van deze ijstijd is vergelijkbaar met die van andere ijstijden in de geschiedenis van de aarde. Zoals gesuggereerd werd door Ewing & Donn, lijkt een combinatie van opheffing van continenten, gebergtevorming en thermische isolatie van één of beide polen de enige logische verklaring voor het ontstaan van ijstijden. De grote variaties in de vergletscheringen van de middelhoge breedtes gedurende het Pleistoceen (van een orde van grootte van $\pm$ 40.000 jaar) kunnen veroorzaakt zijn door variaties in de ontvangst van zonnestraling door de aarde, zoals berekend door Milankovitch. Deze theorie wordt ondersteund door de correlatie tussen: 1. variaties in de ontvangst van zonnestraling, 2. ^{18}O paleotemperatuurskurven en 3. zeespiegelschommelingen tijdens het Pleistoceen.

De waargenomen correlatie tussen hoge zeestanden tijdens de interglacialen en de precessie enerzijds en tussen variaties van ^{18}O temperaturen en de helling van de ellips van de aardbaan anderzijds schijnen die theoriën te ondersteunen, waarin aan de invloed van precessie en helling van de aardbaan een verschillend gewicht wordt toegekend. Een mogelijke physische verklaring voor deze verschillende gewichten wordt naar voren gebracht.

INTRODUCTION

During the past two decades it has become clear that the Antarctic ice sheet as well as high-latitude glaciers in the Northern Hemisphere have begun their expansion probably as early as 7 million years ago and that large glaciers already existed a million years ago in Iceland, North America and Argentina. At the same time, abundant confirmation has been found of the hypothesis of continental drift. Accurate radioactive dating and paleotemperature measurements with the $^{18}/^{16}O$ method have furnished quantitative data on Pleistocene and Tertiary temperatures.

In the light of these findings, this paper attempts to review critically ideas on the origin of glaciations. Inevitably, in an area in which much is still uncertain, this review will be somewhat coloured by personal opinions.

Before discussing the possible causes we briefly review in the next chapter the observed facts that have to be explained by any theory on the origin of glaciations.

The review is based on literature post dating 1959. For earlier references we refer to Emiliani & Geiss (1959). For an updated review of the most important literature on Pleistocene and late Tertiary geology we refer to Flint (1971); for general reading about paleoclimatology and possible causes of Ice Ages we refer to the books by Shapley (1953), Brooks (1971), Schwarzbach (1963), Nairn (1964) and Lamb (1971).

THE OBSERVATIONAL RECORD ON GLACIATION

Pre-tertiary Ice Ages

The "normal" climatic state of the Earth seems to be: tropical to subtropical from the equator to the poles (Brooks, 1971). This normal warm situation is at times interrupted by periods on the order of several tens of millions of years during which parts of the Earth's surface are glaciated. Such long periods of variable glaciation we shall call Ice Ages. The shorter periods of maximum extend of continental glaciers within an Ice Age we shall call glaciations.

Table 1 summarizes the Ice Ages in the geological history of the Earth, recognized to date (partly after Holmes, 1965, and Dunn *et al.*, 1971). Of the pre-Tertiary Ice Ages the Carboniferous (Upper Paleozoic) is the best documented. Its abundant traces have been found in South America, South Africa, India and Australia and have furnished one of the first important arguments for the idea that these continents formed one single landmass (Gondwanaland) in the past (Wegener, 1915, 1924; Du Toit, 1937). Paleomagnetic data (Mc Elhinny *et al.*, 1968) show that the centre of the ice cap, which is now located in South Africa, was close to the magnetic south Pole during the Carboniferous (Fig. 1). Theoretical considerations concerning the generation of the Earth's Magnetic field (Elsässer, 1950; Runcorn, 1954; Parker, 1970, 1971) indicate that the average axis of the magnetic dipole is expected to coincide with the rotational axis. Paleomagnetic measurements are therefor expected to give the positions of the *geographic* South Pole. The absence of traces of the Late Paleozoic Ice Age in the Northern Hemisphere is explained by the fact that most of the other land masses were located near the equator at that time, and the North Pole was located in the present Mid-Pacific Ocean. The Late Paleozoic Ice Age probably lasted about 50 million years and the weight of the ice cap may have caused the break-up of Gondwanaland into its present pieces (Gough, 1970).

Of the older Ice Ages shown in table 1, only the Late Precambrian has been well documented. Abundant information comes from Australia (Dunn *et al.*, 1971) where the Late Precambrian Ice Age extended between 750 and 570 million years ago. Dunn *et al.* find that it consisted of at least two major stages of very long duration: the first (Sturtian) stage extended for about 50 million years, while the second (Marinoan) stage extended for approximately 80 million years. Both left immense deposits of glacial sediments (in places 5500 m thick) covering about half of the Australian continent. It was probably the most widespread of all known Ice Ages, as it also left glacial sediments in Britain, Scandinavia, Spitsbergen, Greenland, China and possibly South Africa (cf. Roberts, 1971). Due to its long duration, it is possible that the different maxima were recorded as separate Ice Ages in various parts of the world. For instance, in China four Ice Ages were recorded in the Late Precambrian and one in the Early Cambrian (cf. Dunn *et al.*, 1971).

For Ice Ages preceding the Late Precambrian similar uncertainties exist. From the amounts of sediment deposited however, it seems that each Ice Age also probably lasted for over ten million years.

Tertiary evidence of glaciation

During the Mesozoic (230 to 70 million years B.P.) some 80 per cent of the Earth's surface was covered by oceans and shallow seas. Only continents of low elevation (mostly less than 2.000 m) existed. There were no glaciers and even in the polar regions temperatures probably exceeded 10° C., as no $^{18/16}O$ ocean bottom temperatures lower than 14° C. have been recorded from sediments deposited during these periods (Emiliani, 1961). The absence of coral reefs in polar regions and their widespread distribution in equatorial zones indicate polar temperatures below 20° C. and equatorial temperatures around 29° C. for this period (cf. Newell, 1972). Similar temperatures existed between the Late Precambrian and the Carboniferous (Brooks, 1971). The onset of the Pleistocene glaciations seems to have started more than 30 million years ago and perhaps as far back as 70 million years ago. Paleontological evidence of changes in fauna and flora indicates a temperature decrease of 8 - 10° C. in middle northern latitudes during the Tertiary (Colbert, 1953; Barghoorn, 1953). The $^{18/16}O$ analysis of equatorial Pacific Ocean bottom sediments (Emiliani, 1961) indicates a temperature decrease of Pacific bottom water from 14° C. in Cretaceous, to 11° C. in middle Oligocene, and 3° C. in the late Pliocene time. As this bottom water is presently formed by Antarctic melt-water, the Tertiary temperature decrease suggests that the formation of high-latitude glaciers in the Southern Hemisphere may have already started between 70 and 30 million years ago. During the same period, due to continental drift, many of the shallow Mesozoic seas were being drained and the continental area increased to about 29 per cent of the Earth's surface (the present value) by the late Pliocene time.

Figure 2 shows the gradual Tertiary temperature decrease, as inferred from fossil plants in various parts of the world.

An analysis of 18 Cenozoic subantarctic ocean bottom sediment cores, raised between 90° and 160° W longitude, Margolis & Kennett (1970) found ice rafted detritus in sediments of Eocene (53 to 36 million years) and Oligocene (36 to 22 million years) ago. No ice rafted detritus was found in Lower and Middle Miocene deposits in this area, suggesting that warmer climates prevailed during these time intervals. From Upper Miocene (7 million years ago) on, ice rafted detritus was continuously present in the studied cores. Diversity of foraminiferal species in sediments confirmed these climatic trends; paleoclimatic curves for New Zealand also confirm the Eocene-Oligocene low as well as the Lower and Middle

Miocene high temperatures (references in Margolis & Kennett, 1971). Although these findings agree with the general trends for the Northern Hemisphere (Fig. 2) the middle Miocene high temperature was apparently higher in the Southern than in the Northern Hemisphere. Tertiary transgressions and regressions in Western Europe suggest a relation with the amount of Antarctic ice during this period.

The presence of ice rafted detritus in a core raised from 32° 59' South latitude (87° 57' W.) in Eocene sediments is interesting as even today, icebergs in this region do not reach beyond North than 45° S latitude. This may indicate that, due to continental drift, the position of Antarctica and the surrounding ocean bottom in those times was quite different from today. From the distribution of fossil coral reefs (Newell, 1972), it may be concluded that during the late Mesozoic the equator along these longitudes must have been situated northward from its present position, and the South Pole was located nearer the above mentioned site. The observation that Antarctica was continuously glaciated for the last 7 million years confirms earlier findings by Armstrong *et al.* (1968), and by Hays & Opdyke (1967). Hays & Opdyke found that warm water radiolaria began to disappear about 5 million years ago in subantarctic cores and have been absent in the last 2.4 million years. On continental Antarctica, data from Mc MurdoSound indicate the continuous presence of glaciers for over 4 million years (cf. Flint, 1971: 711 ff.). Mercer (1969) found glacial deposits in Argentina covered by a lava bed more than 2 million years old.

In the Northern Hemisphere, glacial deposits in Iceland about 2 million years old were first noticed by Rutten & Wensink (1960). In Sierra Nevada, California, glacial deposits about 3 million years old were found (Curry, 1966). Herman (1970), studying sediment cores from the Arctic Ocean bottom, found ice rafted detritus in sediments deposited more than 3 million years ago. From the fauna and lithology of these cores, it appears that increased iceberg and shelf-ice production and melting occurred between 2.4 and 0.7 million years ago (Herman, in press). Herman found that the Arctic Ocean was ice free between 2.4 and about 0.7 million years ago after which successive ice-covered and ice-free conditions existed.

The continuous glaciation of both polar caps of the Earth for the past 6 to 7 million years, together with the presence of Antarctic glaciers as early as Eocene, make the present (late Cenozoic) Ice Age similar in duration to the other large Ice Ages listed in table 1.

The Pleistocene glaciations

Mid latitude glaciation seems to have started not much earlier than 0.7 million years B.P. and was accompanied by freezing of the Arctic Ocean (Herman, 1970). The increase in glacier ice volume as compared with the present volume, during the maximum of Pleistocene glaciation as estimated by Flint (1971: 84), is given in table 2.

Through sea level lowering by about 100 to 130 meters, the Pleistocene glaciations had profound influence of the distribution of flora and fauna, even in equatorial regions such as the Indonesian Archipelago. There seem to have been at least six large continental glaciations during the Pleistocene (Flint, 1971: 624-625), alternating with interglacial periods during which climates and sea level were similar to present. In the Alps the Pleistocene glaciations were named Würm, Riss, Mindel, Günz, Biber and Donau, which names will be used here. During interglacials, sea level probably never exceeded present levels by more than 6 to 10 meters (cf. Emiliani, 1969), indicating that most of the Antarctic ice cover did not melt. Had the ice cover melted, it would have caused a subsequent rise in sea level of about 60 meters. However, parts of the Greenland ice sheet may have melted, for this would not have raised the sea level by more than 10 meters. All available evidence (Flint, 1971: 715 ff.) indicates that during the past 1.4 million years temperatures on the entire Antarctic continent did not rise above 0° C. The bottom 10 to 15 per cent of the Greenland ice has an age of more than 100.000 years (Dansgaard *et al.*, 1969), which means that it already existed during the last interglacial. Unfortunately, the ages of the Pleistocene glaciations are still a matter of dispute. The range of reliable dating extends back to about 120.000 years. Figure 3 shows that the $^{18/16}O$ isotopic temperature curve, as derived from Caribbean and Mediterranean bottom sediments (Emiliani, 1969), agrees well with the $^{18/16}O$ determinations from a core of Greenland ice, dated by the ^{14}C method (Dansgaard *et al.*, 1971), as well as with data from continental Europe and North America, dated by various radioactive isotope methods. Simultaneously with the Pleistocene glaciations of the Northern Hemisphere, parts of the Southern Hemisphere were also glaciated, notably southern Chile and Argentina and the southern part of New Zealand (cf. Flint, 1971: 687-710).

For the past 400.000 years the most reliable continuous record available is Emiliani's (1966, 1969) generalized $^{18/16}O$ isotopic temperature curve obtained from Caribbean deep-sea sediment cores (Figure 4). Dating was carried out with the ^{14}C and $^{231}Pa/^{230}Th$ methods. In the high temperature parts of the curve, the relative maxima coincide very well independently dated time intervals of interglacial high sea levels (Broecker *et al.*, 1968; Emiliani, 1969; Emiliani & Rona, 1969), which are indicated by arrows. The curve reflects the variations in the surface $^{18/16}O$ ratio at low latitudes. According to Dansgaard's and Tauber's (1969) modification, some 70 per cent of the $^{18/16}O$ variation in ocean water does not reflect water temperature, but is determined by the amount of continental glaciation. At times of maximal continental glaciation, the ^{18}O content of the oceans was highest in as much ^{16}O enriched water was removed from the ocean and precipitated on land and tied up in glaciers. The temperature minima in Emiliani's curve would therefor probably reflect the maximum extend of continental glaciers rather than minimum ocean water temperatures. As we are mainly concerned with the dating of the glaciations, we have represented Emiliani's curve in its original unmodified form. The curve shows that during the last 400.000 years the amount of glacier ice varied with a periodicity of roughly 40.000 years (Emiliani & Geiss, 1959; Emiliani, 1966; Broecker, 1966 ; Van den Heuvel, 1966a). Apart from the Würm (Weichsel, Wisconsin) Glaciation, the correlation of continental glaciations with the minima of Emiliani's curve is not yet well established.

THE PROBLEM OF CAUSES

Requirements for a theory

From the evidence in the foregoing section, it appears that any theory on the origin of glaciations should explain two facts:

(1) The high-latitude cooling for periods on the order of 10 to 100 million years
(2) For the present (Late Cenozoic) Ice Age: the large variations in the amount of continental glacier ice, on a timescale on the order of 40.000 years.

As equatorial temperatures apparently did not drop by more than a few degrees C. since the Mesozoic, while the polar temperatures decreased by more than 14^o C. (see chapter "Tertiary evidence of glaciations"), the Ice Age condition seems to mean a *steepening of the temperature gradient between the equator and the poles, rather than a uniform cooling of all parts of the Earth* (cf Brooks, 1971).

Furthermore, it should be explained that during the Pleistocene the amount of glacier ice apparently varied between two well-defined limits: the *interglacial* stages with ice sheets only on Antarctica and (parts of) Greenland, and the *glacial* stages in which the Scandinavian mountains, Canada and the northern United States, as well as New Zealand and the southern Andes, were centers of large continental ice sheets.

The heat balance of the Earth and possible cosmical and terrestrial factors affecting climate

The all-over heat balance of the earth is of primary importance to the problem of climatic change. This balance is largely determined by the albedo, which in turn is influenced by the distribution of oceans and continents, by cloudiness, sea roughness and by the amount of glaciated surface area. Table 3 lists the albedos of various types of surface. The present over-all albedo of the Earth, as determined from the reflection of Earth light by the moon, is about 35 per cent (Fritz, 1949; Danjon, 1954; Franklin, 1967). (We do not use values obtained from satellite observations, as these might be less reliable, cf De Vaucouleurs, 1970). Sixty five per cent of the radiation not directly reflected is absorbed in the atmosphere, oceans, and continents, and is finally radiated outward, mostly in the form of long-wave radiation. It is this process of absorption and re-emission which determines the equilibrium temperature of the Earth. It is clear that changes in the albedo will affect the heat balance and the temperature equilibrium. The present heat balance of the Earth, according to Möller (1950), is depicted in figure 5. According to calculations by Wexler (1953) an increase of the albedo from 35 to 43 per cent will change the heat balance in such a way that the mean equilibrium temperature will drop by about 8^o C.; hence, a decrease by about 1^o C. for 1 per cent change in albedo. Furthermore, Simpson (1938) calculated that a $\pm$ 10 per cent change in solar radiation will induce changes of $\pm$ 6^o C. in the equilibrium temperature. Although these calculations are only rough, first order approximations, they show that climatic changes, and possibly glaciations, may be induced by terrestrial as well as by cosmical factors.

The following cosmical and terrestrial factors have been suggested as possible causes of glaciations:

(1) COSMICAL

- (a) Secular changes in the Earth's orbit (Milankovitch, 1920; 1930, 1941);
- (b) Variations in the energy output of the Sun (Öpik, 1953a, 1953b, 1965);
- (c) The passage of the solar system through an interstellar cloud (cf. Krook, 1953);
- (d) Variations in solar activity (Wexler, 1953; Willett, 1953; Bray, 1968, 1971);
- (e) Variations in the tidal strength (Petterson, 1914).

(2) TERRESTRIAL

(a) Mountain building and continental uplift, which may have changed the atmospheric circulation pattern (cf. Emiliani & Geiss, 1959);
(b) Continental drift, which may have caused isolation of the poles from the oceanic circulation system (cf. Ewing & Donn, 1956, 1958);
(c) Changes in the atmospheric carbon-dioxyde content (Roberts, 1971)

or

(d) In the amount of vulcanic dust in the atmosphere (Wexler, 1953).

As to the terrestrial factors, the factors 2(a), (b) and (d) are due to the same cause, *viz.* continental drift. These factors have about the right time scale for explaining the large Ice Ages. (We define as "time scale" the time interval required for the development of significant changes, e.g. for a continent to moove over a distance comparable to its size). However, a decrease in the carbon-dioxyde content of the atmosphere ("anti greenhouse effect") may only have been effective during the Late Precambrian Ice Age, as the main phase of atmospheric carbon-dioxyde reduction occurred between 2 billion and 500 million years ago (Cloud, 1968; Cloud & Gibor, 1970). If we were to adopt this effect as a cause of glaciations, it might imply that one would have to look for a different cause for each individual glaciation. Because this does not seem to be a sound scientific principle, we will not consider variations in atmospheric carbon dioxyde content as a general cause of glaciation. As to cosmical factors, the interstellar cloud hypothesis seems unlikely because the hypothetical cloud which would have caused the Würm (Weichsel) Glaciation could not have travelled over a distance larger than several light years and thus it should still be observable. However, this is not the case. The evolutionary variations of the solar energy output, as suggested by Öpik seems very unlikely (Van den Heuvel, 1966b, 1966c); particularly the required initial solar hydrogen content of 30 per cent is entirely unacceptable [+]). For these reasons the only reasonable causes remaining are 1(a), (d) and 2(a), (b), (d) or a combination of these. We will therefor consider them in more detail.

Cosmical causes of climatic change

A. Solar activity

The climatic effects of solar activity are still poorly understood. Some evidence of a correlation between climate and solar activity during the past 2.500 years was found by Bray (1968, 1971). Dansgaard *et al.* (1969) found

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[+]) Recently, the negative results of efforts to detect neutrinos from the solar interior have led a number of astrophysicists to reconsider the possibility of instabilities in the solar core. These considerations (Dilke & Gough, 1972; Ezer & Cameron, 1972) suggest that possibly, with time intervals of the order of 250 million years instability and mixing occurs in the solar core. This would cause a decrease in the solar energy output by about 5 per cent over a time interval of the order of 6 million years. Hence, it might cause an Ice Age of considerable duration. However, before conclusions about this interesting possibility can be drawn, the physics of the suggested instability process should be carefully worked out in detail.

in the $^{18/16}O$ record of Greenland ice, periodicities of 120 and 940 years which they described as due possibly to solar activity. Nevertheless, such activity would have had only small climatic effects as the temperature changes involved most probably did not exceed a few degrees Centrigrade (the average reduction in mean temperature during the "Little Ice Age" of the 17th - 18th centuries). Therefor, the solar activity seems to be an unsufficient explanation of a drop of 14° C. in polar temperatures since the Mesozoic. However, it may have triggered increased glaciation on an already cool Earth. An extensive, though rather speculative, discussion of solar activity as a possible cause of glaciation was given by Willett (1953). Triggering effects will be considered in the next chapter.

B. Variations in insolation produced by secular changes in the Earth's orbit.

These variations do not affect the total amount of *yearly received* solar radiation on the entire globe; they only influence the *distribution* of solar radiation over different latitudes. Milankovitch (1941) systematically explained how, at different latitudes, the insolation varies, as a consequence of secular variations of the elements e, ε and Π of the Earth's orbit, due to the variable gravitational attraction of other planets. Here e denotes the orbital excentricity (see figure 6), ε is the obliquity of the ecliptic plane (= angle between the ecliptic and the equatorial plane), and Π is the longitude of the perihelion (= angle, seen from the Sun, between the directions to the equinox γ and to the perihelion P, counted in the direction of the Earth's orbital motion).

The insolation variations can be computed accurately as far back in history as one wishes. According to Van Woerkom's (1953) revision, e varied during the past million years between 0.000 and 0.053 in a period of roughly 96.600 years; ε varied between 21°.8 and 24°.4 in a period of nearly 41.000 years; and Π increased by 360° in a period ranging from 13.500 to 29.000 years, with an average of 21.000 years. The main contribution to the last-mentioned periodicity comes from the precession (P = 25.700 years); the remainder is due to the motion of the line of apsides in the ecliptic plane.

THE ASTRONOMICAL CLIMATE

The orbital variations have two effects:

(1) the ε-variations have equal effects for both hemispheres. If ε is larger than at present, the higher latitudes (above 43°) in both hemispheres receive more solar radiation during the year then when ε is smaller (this can be easily understood by taking the poles as example). At the poles an increase of ε by 1° gives an increase in summer isolation of 4.02 per cent, at 70° latitude, of 3.18 per cent. The situation with minimal ε is therefor favourable for the occurence of increased glaciation at high latitudes.

(2) the Π-variations: we assume $e \neq 0$. If $\Pi = 0°$, summer and winter have equal length on both hemispheres (see figure 6, we define the astronomical summer as the time interval during which the Sun is above the equator). However, 5.250 years later, when $\Pi = 90°$, the northern summer will last longer than the winter. The northern summer will be long and cool, the winter short and mild. The southern summer will be warm and the winter cold. The difference in duration between summer and winter is

$$\Delta T = \frac{\text{[illegible]}}{\pi} \sin \Pi .\ 365.24 \text{ days} \qquad (1)$$

For $e = 0.05, \Pi = 90$ or 270°, one has $\Delta T = 25$ days. If $\Pi = 180^{\circ}$, there will again be no difference between the two hemispheres. If $\Pi = 270^{\circ}$, conditions are the reverse of conditions for 90°: the northern summer will be short and hot, the southern long and cool.

The effects of the Π-variations vary with latitude and are strongest at *lower* latitudes (see figure 7).

THE OCCURRENCE OF ICE AGES

Milankovitch postulated that the *mean summer insolation* determines the growth or melting of glaciers. Thus during periods with hot summers, snow which fell during would melt. Conversely reduction of summer temperature would favour preservation and growth of glaciers. Therefor a situation with ε low, $\Pi = 90^{\circ}$ and e large is, according to Milankovitch, most favourable for the occurrence of Northern Hemisphere glaciation. The situation with ε low, $\Pi = 270^{\circ}$ and e large is most favourable for a Southern Hemisphere glaciation. As a consequence of the different periodicities in the variations of ε, e and Π, the situation of extreme insolation are expected to occur at irregular intervals of time.

Computations by Milankovitch (1941) show that at latitudes higher than about *70°* the insolation variations are mainly controlled by the –variations. Hence, roughly a 41.000 year periodicity in insolation occurs (see figure 7), with simultaneous extremes for the Northern and Southern Hemispheres. On the other hand, the Π-variations dominate below about 40° latitude. Therefor Southern Hemisphere maxima occur on the average 10.500 years later than Northern Hemisphere maxima (see figure 7). Between 40° and 70° latitude no clear correlation between Northern and Southern insolation curves is found. Milankovitch postulated that the insolation variations at 65° N (where most of the Pleistocene ice sheets were located) were the main contributors to glaciation. Here the ε-variations are still somewhat dominant over the Π-variations and roughly a 41.000 year periodicity occurs in both hemispheres (cf. Van Woerkom, 1953). The magnitude of insolation variations at 65° N can be judged from the fact that in extreme conditions the mean summer insolation could be reduced to the amount presently received at 82° N, or increased to that presently received at 60° N. This indicates that *the effects are not small.*

C. Variations in tidal strength

Owing to changes in the moon's orbit, the tidal strength changes with a periodicity of about 1.800 years. Petterson (1914) found evidence for the occurrence of severe climatic conditions during periods of strong tides (e.g. the 15th to 18th century) and milder conditions during periods of weak tidal action (e.g. around A.D. 500). Petterson suggested that during periods of strong tides, the tidal waves carry warm Atlantic Ocean water into the Arctic Ocean, causing accelerated iceberg production and spread of pack-ice to lower latitudes. The subsequent cooling of surface ocean water will cause extreme climatic conditions on adjacent continents. Karlstrom (1955) found a 3.500 year periodicity in the extend of the Laurentide ice sheet. Such a periodicity is almost equal to two 1.800 year periods, suggesting a possible relation with tidal strength.

Possible correlations between Pleistocene temperatures and astronomical periodicities

As noted above, Emiliani's generalized temperature curve shows a periodicity of about 40.000 years. This period is almost equal to the period variation of the obliquity of the plane of the ecliptic (Emiliani, 1966; Broecker & Van Donk, 1970). Van den Heuvel (1966a) noted that a period of approximately 12.000 to 13.000 years was also present in Emiliani's generalized curve, and suggested the precession as a possible cause. Later, the same period of 13.000 years was found by Dansgaard *et al.* (1969) in the $^{18}O/^{16}O$ content of the Greenland ice cap. In this ice cap periodicities of 120 and 940 years were also found (cf. figure 3), which were ascribed as due possibly to solar activity. It should be noted, however, that the 940 year periodicity almost equals half the periodicity of tidal strength. Broecker *et al.* (1968) and Emiliani (1969) found that the *interglacial* high sea levels coincide very closely with the times at which the perihelion of the Earth's orbit coincides with the Northern summer solstice (arrows figure 4). Emiliani suggests that this second order oscillation of his temperature curve is due mainly to significant melting of the Greenland ice cap after interglacial conditions are established (If melting of the Antarctic were the main cause, coincidence of high sea levels will be expected when the perihelion *coincides with the Southern summer solstice*).

Veeh & Chappel (1970) found a correlation between variations in sea level over the past 230.000 years (as derived from uplifted coral reef terraces in New Guinea, dated with the ^{14}C and ^{230}Th methods), and variations in insolation at 45° Northern latitude. The latter variations are mainly regulated by the precession, which seems to confirm Emiliani's findings. These observations indicate that Pleistocene temperatures were in some way influenced by variations in summer insolation (cf. figure 3).

The importance of insolation variations as a cause of glaciations

The variations in the Earth's orbit have continued throughout the Earth's history and were apparently unable to induce glaciation during epochs when polar temperatures were high, such as the Mesozoic. As these variations do not affect the total amount of yearly received solar radiation, it is not expected that they would cause large temperature changes on the entire globe. Moreover, with periodicities of less than 100.000 years, insolation variations are ruled out as a cause of high-latitude glaciation during periods of 10 to 100 million years. As a prime cause of the Ice Ages such variations cannot be of importance. On the other hand, on an Earth with glaciated polar caps they may induce an increase or a decrease in the amount of polar ice. Thus, by means of the albedo effect, insolation variations might possibly trigger the Earth to settle at a lower mean temperature for some time. We will consider this possibility in more detail in the chapter "Possible causes of the Pleistocene glaciations".

Terrestrial factors

A. Continental uplift and mountain building

Large Ice Ages have only developed during periods of high land elevation and mountain building (cf. Emiliani & Geiss, 1959). This holds true for the late

Cenozoic as well as for the Carboniferous Ice Age. Uplift of continents since the Late Cretaceous increased the continental area above sea level from less than 20 per cent to 29 percent at the present time (cf. Brooks, 1971; Newell, 1972). Greater atmospheric turbulence due to increased global relief may have caused ocean water evaporation and cloudiness, thus increasing the Earth's albedo (table 3). Furthermore, the presence of high mountains favours the formation of glaciers, even in tropical areas. The largely latitudinal direction of the Eurasian mountain chains (which were all formed since the Late Cretaceous) also prevents atmospheric heat transport from tropical to polar regions in these parts of the world. It is clear, therefor, that during Mesozoic times, with a small continental area and only low land elevations, the situation was extremely favourable for the development of warm "maritime" climates all over the world, whereas during the Tertiary conditions became gradually favourable for the development of continental climates, with increased seasonal contrasts and reduced yearly mean temperatures, especially on continents. Although uplift and mountain building seem to be necessary conditions for the occurrence of glaciation, they alone do not seem to be sufficient, as periods of high land elevation and mountain building have also existed without inducing glaciation. During the Devonian (400 - 350 million years ago) for instance an epoch of increased uplift existed without glaciation. It did, however, induce cooling, as evidenced by a sharp reduction in coral diversity (Newell, 1972). The Caledonian orogeny (Silurian) was not accompanied by glaciation. According to Ewing & Donn (1956a, 1956b) the additional prerequesite (apart from uplift) that has to be fulfilled for a glaciation to occur is isolation of the poles from the ocean heat exchange system.

B. Continental drift and thermal isolation of the poles.

As the heat capacities of equal volumes of water and air have a ratio of a factor of about 3.000, it is clear that the oceans have an enormous heat storage capacity in comparison with the atmosphere. Most solar heat is absorbed in the oceans in a belt around the equator, from there it is distributed towards the poles by ocean currents. On their way back these currents carry cold Arctic water towards the equator, thus continuously reducing the temperature gradient between the equator and the poles. In as much as ocean water temperature determines the air temperature in the surroundings, warm currents induce mild winters and little seasonal contrast in coastal areas, even within the polar circle (e.g. northern Norway), whereas cold currents may induce severe winters even at middle latitudes (e.g. southern Chile).

Ewing & Donn argue that the main cause of the Tertiary temperature decrease at high latitudes was that, due to continental drift, the polar regions became isolated from the oceanic heat exchange system. Further they contend that if the poles were located in open oceans (such as during the Mesozoic) warm ocean water currents will be able to reach them, thereby keeping the polar air temperatures above freezing all year long, even though the amount of winter solar radiation in these regions is extremely low. If, on the other hand, a large continent (such as Antarctica) is located at the pole, or if a pole is surrounded by continents (e.g. North Pole at present) ocean currents will not be able to reach the polar regions. Consequently the polar climates will be regulated by insolation, which is low in summer and absent in winter. Cooling of polar regions, to below freezing would result and glaciation would ensue. Thus, thermal isolation of the poles will cause the establishment of a large temperature gradient between the equator and the poles, while free access of ocean water to the poles will reduce temperature gradients. Confirmation of the importance of thermal isolation of a pole comes from the fact that the Carboniferous Ice Age also occurred when a large continent (Gondwanaland) was located at the South Pole. Other epochs of continental uplift probably did not always induce glaciations because the poles were freely accessible to warm ocean currents, which prevented them from cooling below freezing point. It should be emphasized that, although for polar isolation, continental drift no doubt played an important part, uplift must also have played a considerable part. The Early Tertiary uplift of the Bering Strait for example closed off the access to the Arctic Ocean for long time intervals (cf. Flint, 1971: 538). With a depth of only 40 meters the Bering Strait is still practically closed for oceanic heat exchange.

Most probable causes of the Large Ice Ages

Having investigated the possible cosmical and terrestrial mechanisms, we found that all known cosmical mechanisms are insufficient to cause cooling of polar regions by over 14^{o} C., for periods on the order of 10 to 100 million years +). From the arguments presented in the foregoing paragraph, and in view of the timescales involved, it seems most likely that continental uplift, together with thermal isolation of one or both poles, was the main cause of large Ice Ages. On the other hand, these terrestrial mechanisms have timescales far too large to explain the alternating glacial and interglacial stages, with a periodicity of roughly 40.000 years.

Since many theories have been proposed to explaining these "short-term" climatic variations, we will consider them in a separate section.

POSSIBLE CAUSES OF THE PLEISTOCENE GLACIATIONS

Before dealing with specific theories, we shall briefly review the relevant observations on the growth and development of continental ice sheets during the Pleistocene.

The role of mountains, precipitation, melting and albedo

The Northern European ice cap started to form on the Scandinavian mountains whence it invaded the lowlands up to Minsk (Russia) to the east, and the Netherlands to the south. Figure 8 illustrates the development of the Scandinavian ice cap according to Flint (1971: 598). In North America, Argentina and New Zealand also the ice cap first formed on continental mountains and elevated plateaus, and from there invaded the lowlands and fused to form gigantic ice sheets. In the terminal phases, the sequence of events took place in reverse direction, the mountains being deglaciated last. The location of all major Pleistocene ice sheets close to open oceans (Siberia did not have much of an ice cap) stresses the importance of precipitation. Glaciers can grow only if there is a net excess of snowfall over melting during the year. Reconstruction of wind directions during the Pleistocene glaciations (e.g. from the direction of windblown sand dunes (cf. Flint, 1971: 244-250)) indicates that the prevailing wind directions did not deviate much from the present day. The predominantly westerly winds in Northwestern Europe, and the southwesterly winds over the eastern

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+) see note on page 60.

and midwestern United States, carry moist oceanic air masses far across the continents. On their way over mountains they unload their moisture in the form of snow. The growth of glaciers may result from either (a) increased precipitation or (b) reduced melting. At present precipitation in Scandinavia is already quite heavy (300 cm per year in southern Scandinavia), hence a large increase over the present amount does not seem very likely. As melting occurs mainly during the summer, a decrease in mean summer temperatures maintained over a sufficiently long period of time might be sufficient for inducing a net growth of glaciers. Some areas of the world are indeed so critical that a small decrease in mean summer temperature would be sufficient to induce glaciation. (Barry (1966) estimates from the rates of precipitation and melting that a decrease of 3.3 degrees C. in the mean temperature of Labrador-Ungava, maintained over 20.000 years, would be sufficient to build up a 2.000 m thick ice cap. Under present day conditions with polar ice caps and mountain glaciers, relatively small changes in mean summer temperatures would probably be sufficient to induce extensive continental glaciations. Furthermore, if glaciers with a reflectivity of 50 to 80 per cent were to replace land and water surfaces with a reflectivity of 8 to 15 per cent, the heat intake of the Earth would be reduced and further cooling would ensue. This in turn would induce further growth of glaciers (see "Cosmical causes of climatic change"). By such a self-amplifying *albedo-effect*, a relatively small change in cosmical or terrestrial parameters may *trigger* the onset of extensive continental glaciation. This *essentially non-linear behaviour* of ice and glaciers, requiring only a relatively small temperature drop as a trigger for inducing a large glaciation, plays an important part in most theories on the origin of the Pleistocene glaciations.

Theories for the Pleistocene glaciations

In view of the difficulties involved in non-linear calculations and due to the complexity of the problem involving irregularly shaped continents and relief, coupling between oceanic and atmospheric circulation and heat exchange, evaporation, precipitation, albedo etc., all existing theories are descriptive and by no means sufficiently quantitative. As the time for realistic non-linear climatological computations seems to be still far off, objective evaluation of the different theories is difficult. The only check on these is by comparing their predictions with the observed climatological record of the Pleistocene. We shall to do this by reviewing three important heories.

The Ewing & Donn theory. In this theory, the Arctic Ocean is the main regulator of the Pleistocene glaciations (similar cyclic theories have been proposed with the Arctic Ocean playing a less crucial role, e.g. cf. Willett, 1953). According to Ewing & Donn, if the Arctic Ocean was ice-free, evaporation would cause increased precipitation on the surrounding continents. Mountain glaciers wouldgrow and fuse to form large ice sheets. These ice sheets would influence theclimate and atmospheric circulation in their surroundings. Evidence from Greenland and Antarctica indicates that very stable anticyclonic conditions exist above a large ice sheet. Above the warmer oceanic regions on the other hand, the atmospheric pressure is generally low. In such a situation off-land winds would prevail which would cause cooling of the surrounding oceans. The cooling of the ocean would also induce glaciation in the Southern Hemisphere.

Due to the drop in the sea level the Gulf Stream would no longer reach the Arctic Ocean and this ocean would finally freeze. This would cause a decrease in precipitation, consequently melting and evaporation of the ice sheets become larger than feeding. From here on the volume of ice sheets begins to decrease, although, due to plastic ice flow, the area may remain constant for some time. During this melting stage the surrounding oceans remain cold and hence no increase in precipitation would occur. When the ocean temperature finally begins to rise, the area of the ice caps would have become too small to have significant influence on climates and melting would continue in spite of increased precipitation. After the melting of the ice sheets the Gulf Stream would be deflected northward again and the Arctic Ocean would also begin to melt. The "interglacial" stage, with a still frozen Arctic Ocean, would correspond to the present situation. When the Arctic Ocean finally becomes ice-free, a new glacial cycle will start.

Although this non-linear picture involving only terrestrial factors, seems attractive, there are a number of problems:

(1) The Arctic Ocean should remain open until the maximum volume of continental ice is attained. However, the maximum of the Würm (Weichsel) Glaciation occurred about 20.000 years ago (cf. Dansgaard *et al.*, 1969, 1971) and from Arctic Ocean bottom sediments it appears that the Arctic Ocean has probably been frozen for the past 70.000 - 100.ooo years (Herman, 1970). The continuous presence of at least part of the Greenland ice sheet over the past 120.000 years also suggests that during this period the Arctic Ocean did not warm up much above its present temperature.

(2) It is hard to see why the ice cover of the Arctic Ocean did not melt immediately after the termination of the last glaciation, some 10.000 years B.P. The present climatic situation, with a frozen Arctic Ocean and glaciated Greenland, has been quite stable for the past 10.000 years.

The Milankovitch theory (with possible modifications). As mentioned in "The importance of insolation variations as a cause of glaciations" (and shown in figure 3), most probably Pleistocene temperatures and high sea levels show periodicities similar to the secular variations in insolation computed by Milankovitch (1920, 1930, 1941) and Van Woerkom (1953). This indicates that insolation variations in some way must have played an important part in the occurrence of the Pleistocene glaciations. Milankovitch attempted with the help of a rough atmospheric model to translate the local insolation variations to local temperature variations. This attemps was criticized by a number of people, notably Simpson (1938) who found that atmospheric temperature variations caused by variations in insolation would be much too small for inducing glaciation. In fact, neither Milankovitch's nor Simpson's calculations were correct as both calculations involved linear approximations, while, as pointed out above, the response of high latitude climates to small temperature changes is essential non-linear. Furthermore, neither of these two authors took all relevant factors (especially the oceans) sufficiently into account. The same holds true for the computations by Shaw & Donn (1968). The latter authors showed that, starting from a realistic atmospheric model, the insolation variations computed by Milankovitch could have induced temperature variations of about $\pm$ 2° C. with respect to the present day temperatures at 65° N. From this Shaw & Donn argue that insolation variations are not sufficient as a cause of glaciations, because the Little Ice Age of the 17th/18th century, which involved a drop in mean temperatures by about 2° C. over one century, did not trigger the onset of a real glaciation. However, this argument is not valid as it shows only that the cumulative effect of a 2° C. temperature decrease *over one century* is insufficient to cause a complete glaciation. Insolation variations would, however, lower the mean temperatures by 2° C. for thousands of years. The cumulative effects in this case, for the oceanic circulation system as well, might be sufficient to induce a large glaciation. In fact the *observed* correlations mentioned in "The importance of insolation variations as a cause of glaciations" strongly suggests that insolation variations were indeed an important trigger in Pleistocene temperature variations. The large amplitudo with a 40.000 year periodicity in Emiliani's curve (cf. also Van den Heuvel, 1966a) together with the synchroneity of Northern and Southern Hemisphere glaciations, suggest that insolation variations at latitudes higher than about 65° had the greatest influence. This seems reasonable for two reasons: (a) at high latitudes many permanent glaciers are present, hence their growth might be rather simply induced, and (b) here secular variations in insolation have the largest amplitudes (cf. "Possible correlation between Pleistocene temperatures and astronomical periodicities").

The precession apparently also influenced Pleistocene climates, as interglacial high sea levels varied with the precession period (Broecker *et al.*, 1968; Emiliani, 1969; Veeh & Chappel, 1970) (the term "precession" here includes apsidal motion, cf. Possible correlation between Pleistocene temperatures and astronomical periodicities"). The high sea levels occurred at times when the perihelion passage coincided with the summer solstice (June) in the Northern Hemisphere, indicating that partial melting of the Greenland ice sheet probably occurred during such times (Emiliani, 1969). Emiliani argues that this ice sheet is more sensitive to insolation changes than the Antarctic ice sheet, as it is not centrally located with respect to the pole and extends to lower latitudes. However, it is not certain that an explanation in terms of local insolation is sufficient. At latitudes higher than 65° the precession has only a minor influence on insolation, whereas at latitudes lower than 40° it has a large effect (cf."Possible correlation between Pleistocene temperatures and astronomical periodicities", figure 7). An alternative explanation might be that when the perihelion passage occurred in June, the increased insolation caused heating of the north equatorial parts of the oceans and induced the Gulf Stream to extend its influence further north. This may have caused increased melting of the Greenland ice. The summer insolation changes due to the precession are as large as 7 per cent and in times of high orbital excentricity may become as large as 15 per cent. Therefor their influence on climates is certainly not expected to be negligeable. In fact, in pre-Pleistocene times, the effects of the precession are found notably in varves of the Tertiary Green River Formation (Bradley, 1929).

Apparently no appreciable melting of the Antarctic ice sheet took place in times when the perihelion passage occurred in December (southern summer solstice). This fact may be due to the entirely different distribution of oceans and continents in the Southern Hemisphere. Antarctica is surrounded by a wide belt of cold ocean water (the Antarctic Convergence); furthermore, in the vast Southern Hemisphere Oceans the currents are much less channelled and restricted by coastlines than in the narrow North Atlantic. For this reason their path and extent will be much less sensative to changes in equatorial heating. These two factors suggest that changes in insolation in the equatorial belt have far less effect on the Antarctic than on the Greenland ice sheet.

It is interesting to note that, in combining the effect of the precession on the equatorial oceans with the effect of obliquity on high-latitude glaciation, one arrives at Broecker's (1966) semi-empirical modification of Milankovitch's theory, in which precession and obliquity are given different weights. The above mentioned correlations indicate that such a theory seems most plausible.

The occurrence of *half* the precession period in Emiliani's and Dansgaard's $^{18}/^{16}O$ records (cf. "The importance of insolation variations as a cause of glaciations" and figures 3, 4) seems puzzling. The $^{18/16}O$ cycle in both records is well in phase with the record of extremes in the June Sun-Earth distance (cf. Dansgaard *et al.*, 1969; Van den Heuvel, 1966a). In terms of Dansgaard & Tauber's (1969) modification of Emiliani's curve, maximum $^{18/16}O$ means a maximum volume of continental ice. Maximum June Sun-Earth distance is expected to coincide with maximum glaciation on the Northern Hemisphere and minimum June Sun-Earth distance with maximum glaciation on the Southern Hemisphere. The double wave therefore indicates that at maximum Northern as well as at maximum Southern Hemisphere glaciation the total volume of continental ice was apparently larger than at intermediate periods. Its occurrence therefore does not conflict with Milankovitch's theory.

Wilson's 1964 theory assumes cyclic surging of the Antarctic ice sheet. In a growing ice sheet the vertical temperature gradient is mainly determined by the rate of precipitation (Robin, 1962). A drop in precipitation will reduce the temperature gradient and may cause the glacier bottom the reach the pressure melting point. In such a case, the glacier may start to advance at high speed. This kind of glacier instability has often been observed, notably in Spitsbergen (Hollin, 1965). Wilson's theory suggests that after a period of growth, a drop in precipitation in Antarctica triggers the ice sheet to become instable and to flow out over the surrounding ocean. It then covers an area four times larger and its thickness is reduced from 2.000 to 500 meters. Due to the sudden albedo increase and the cooling of the oceans, glaciation would also spread to the Northern Hemisphere. The ice shelf would displace enough water to cause a sudden 20 to 30 m rise in sea level.

After the ice shelf has melted the oceans warm up and finally the northern glaciation would disappear. During interglacials the Antarctic ice sheet would slowly build up again to a thickness of over 2.000 meters, when a drop in precipitation may again cause it to surge. According to Wilson, the decrease in precipitation might be due to insolation variations. Van den Heuvel (1966d) pointed out that in such a case a coincidence between Nothern Hemisphere summer insolation minima and a northern (as well as southern) glaciation is to be expected. The reason for this is that low precipitation in Antarctica is expected in times of minimum winter insolation, which coincides with times of minimum summer insolation in the Northern Hemisphere.

The attractive aspects of this theory are:

(1) It gives a simple explanation for the synchronism of Northern and Southern Hemisphere glaciation;
(2) It also explains simply how the Earth, despite the albedo effect, could have returned to interglacial conditions after glaciation had been established. This is very important, as none of the other theories gives a simple explanation for this occurrence;
(3) It does not conflict with observed astronomical periodicities in the Pleistocene as recorded by $^{18/16}O$.

However, one may wonder whether surging on the scale of the entire Antarctic ice sheet is possible. Furthermore, the Pleistocene $^{18/16}O$ record, showing the effects of precession as well as obliquity, indicates gradual rather than sudden climatic changes. A crucial test for the theory is to examine whether each glaciation was preceded by a sudden sea level rise. Although the present evidence makes interglacial high sea levels exceeding 10 meters above the present level unlikely (Emiliani, 1969), some evidence of sudden sea level rises by the end of interglacials may exist (Hollin, 1965). Clearly, further research for testing this interesting theory is required.

Other theories. For a brief review of other theories concerning Pleistocene glaciations we refer to Flint (1971: 789-809). Most of these theories involve some modifications of Milankovitch's theory (Broecker, 1966), or involve unknown factors such as solar activity during the Pleistocene (cf Willett, 1953). One of the omissions in all existing theories that involve insolation changes is the neglect of the influence of low-latitude insolation variations on the ocean current system. The merit of Ewing & Donn is to have pointed out the importance of the oceans in connection with glaciation.

SUMMARY AND CONCLUSIONS

1. The occurrence troughout the history of the Earth of periods of high latitude glaciation on the order of 10 to 100 million years (table 1), alternating with warm periods on the order of 100 to 200 million years, is most probably due to a combination of continental uplift and isolation of one or both poles from the oceanic heat exchange system in the sense of Ewing & Donn. Such an explanation agrees with all observational evidence of the well documented Upper Paleozoic and Late Cenozoic (present) Ice Ages.

2. No cosmical causes of climatic change with time scales on the order of 10 to 100 million years are known [+]).

3. The present situation with permanent ice sheets in Greenland and Antarctica has lasted throughout the Pleistocene and has two fairly stable climatic states: the "glacial" state in which large parts of the North American, Eurasian and South American continents are glaciated and the "interglacial" (present) state. These two states alternate with a roughly 40.000 year periodicity. The switch-over from one state to the other can be triggered by relatively small changes in high latitude temperatures. The observed correlation between Pleistocene isotopic temperatures and variations of high-latitude summer insolation in both hemispheres suggests that the triggering is provided by secular variations in summer insolation.

4. The roughly 13.000 year modulating period in the $^{18/16}O$ ratio of Greenland ice and of Caribbean deep-sea cores, as well as the occurrence of interglacial high sea levels at times when perihelion passage and northern summer solstice coincides (figures 3, 4), suggests that the precession played a part. Variable heating of ocean water in the equatorial belt may have induced these lower amplitude climatic variations at high northern latitudes.

5. The small-amplitude 940 and 120 year periodicities in the $^{18/16}O$ ratio of the Greenland ice indicate that variations in tidal strength and solar activity may cause minor climatic changes.

6. Tertiary transgressions and regressions in Europe are probably related to variations in glaciation of the Antarctic continent.

[+]) see note on page 60.

ACKNOWLEDGEMENTS

We are grateful to Drs. W. Dansgaard, E. Emiliani, D. I. Gough and R. F. Flint for the permission to reproduce figures from their publications, and to Dr. Y. Herman for valuable comments on the manuscript.

Ice Age	Time (million of years)	Main glaciated areas
Late Cenozoic (present)	7 to 0 (50 to 0 for parts of Antarctica)	Antarctica, Greenland and, periodically, parts of Northern Eurasia, North America, South America and New Zealand.
Upper Paleozoic	250 to 200	Australia, South Africa, South America, India, Antarctica.
Late Precambrian	750 to 700 (Sturtian) 650 to 570 (Marinoan)	Australia, Spitsbergen, North Atlantic area, USSR, Africa, North-Eastern Asia, possibly South America
Huronian (or part of the Late Precambrian Ice Age ?)	800 (?)	Cobalt, Ontaria; Witwatersrand, Transvaal.
Bothnian	1000	Finland, Western Australia (?)
Damara	1200 (?)	Chuos District, Southwest Africa.
(no name)	1500 (?)	Medicine Bow Mountains, Wyoming.
Gowganda	2200	Southern Canada

TABLE 1. Ice Ages in the history of the Earth (partly after Holmes, 1965, and Dunn *et al.*, 1971)

Ice sheet	Volume (10^6 km^3 water)		Sea level equivalent (m)	
	Today	Glacial Age	Today	Glacial Age
Antarctica	21.50	23.84	59	66
Greenland	2.38	4.01	6	11
Laurentide ice sheet (North America)	-	27.01	-	74
Cordilleran ice sheet (North America)	-	3.25	-	9
Scandinavian ice sheet	-	12.21	-	34
All other ice	0.18	1.04	0.5	3
Total	24.06	71.36	65	197

TABLE 2. Estimated volume of land ice today and during a maximum of Pleistocene glaciation (somewhat speculative, after Flint, 1971: 84)

Type of surface	Albedo (per cent)
vegetation, ground	8 to 15
calm sea	8
rough sea	40
clouds	60 to 70
ice and snow	50 to 80

TABLE 3. Albedo for various types of surfaces (after Fritz, 1951, and Dietrich & Kalle, 1957: 126)

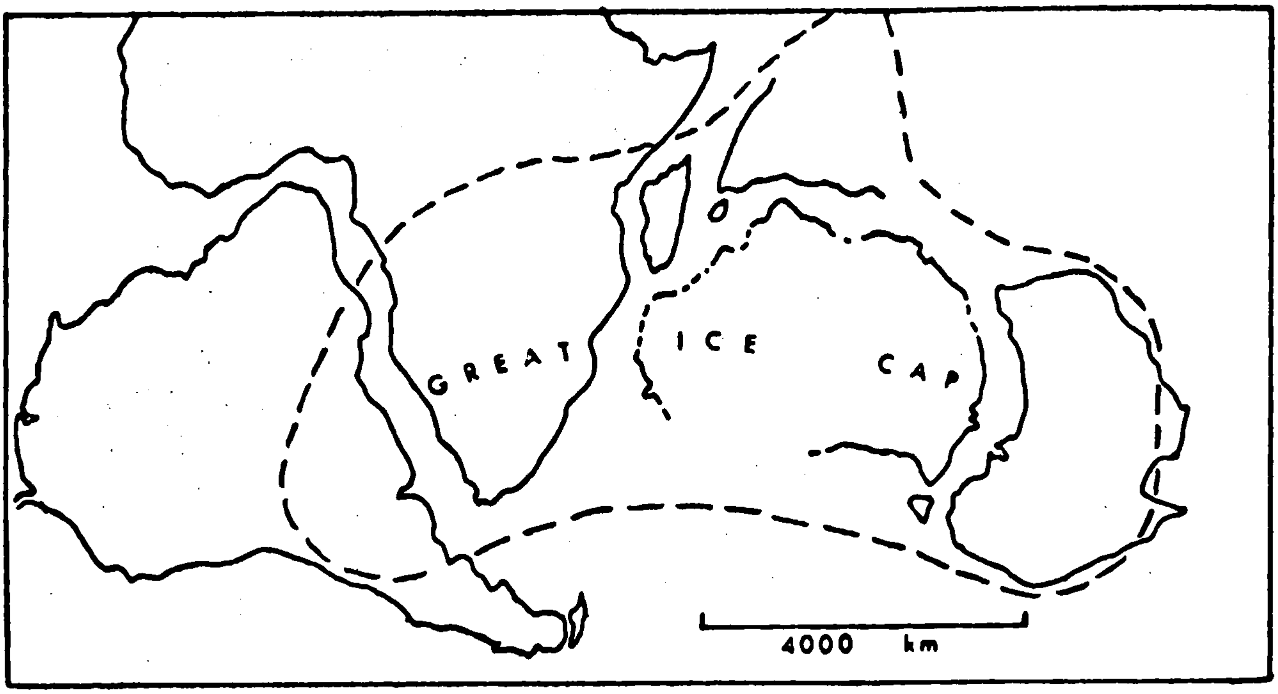


Figure 1. The Upper Paleozoic (Carboniferous) ice cap covered parts of South Africa, South America, India, Australia and Antarctica; at that time these continents most probably formed one single landmass, Gondwanaland (after Gough, 1970).

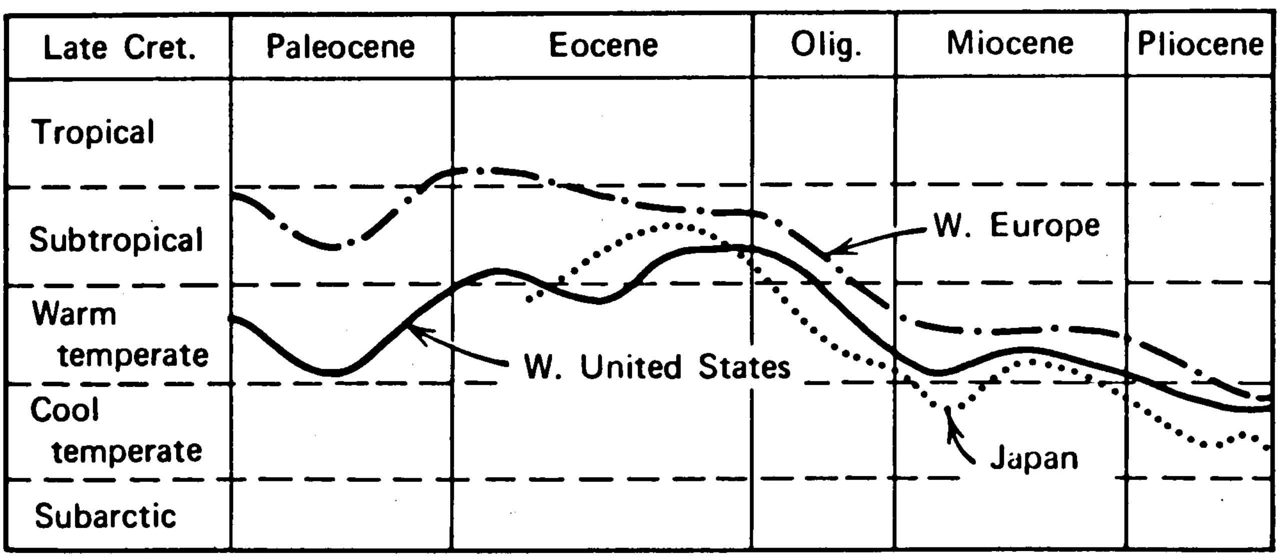
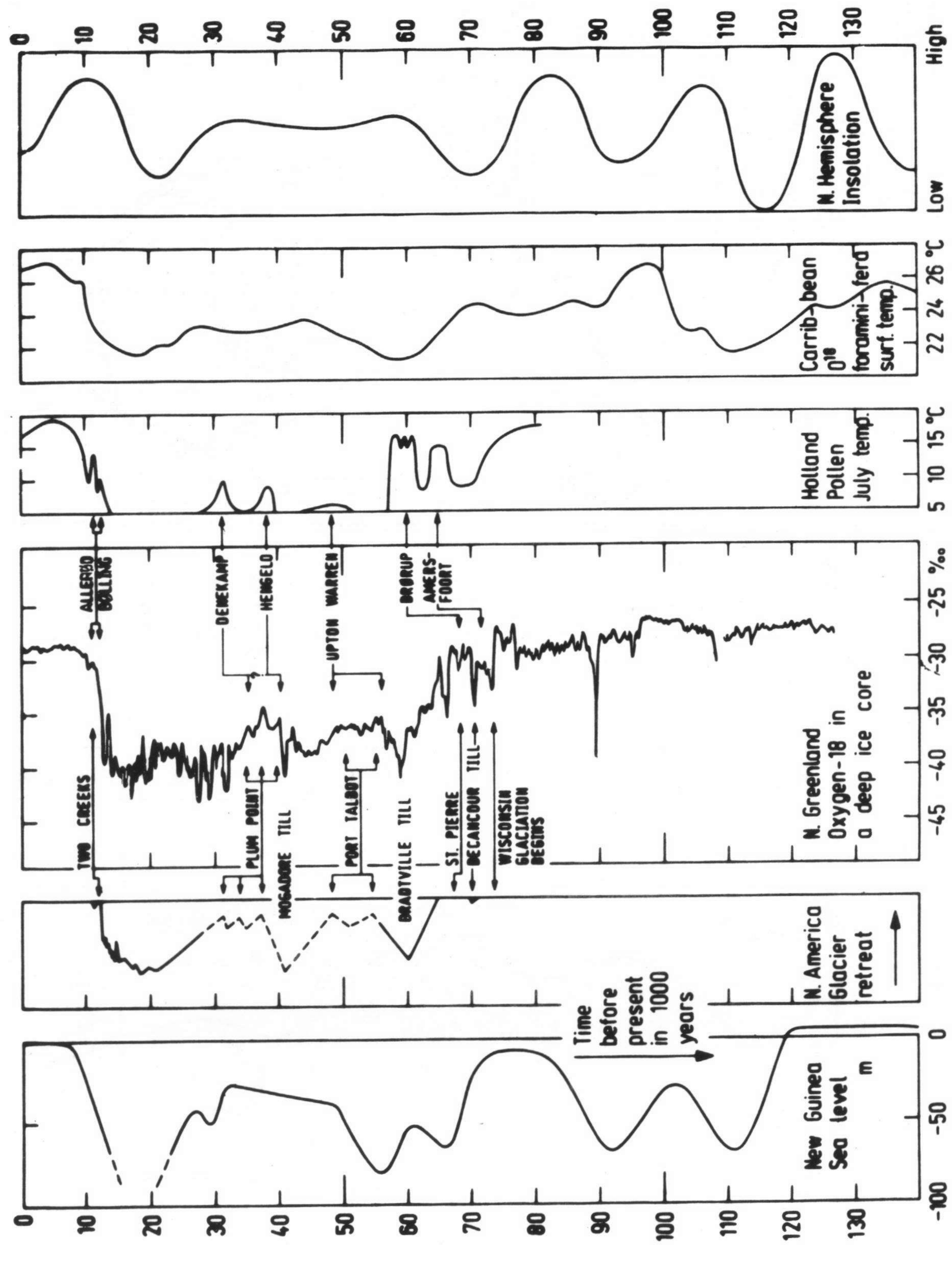


Figure 2. Climatic cooling through Cenozoic time, inferred from fossil plants in three parts of the world (adapted from Flint, 1971, figure 16-3, and Margolis & Kennett, 1970, figure 2).


N. Hemisphere Insolation
Low
High
f
Carrib-bean
O^{18}
foramini-fera
surf. temp.
22 24 26 °C
e
Holland
Pollen
July temp.
5 10 15 °C
d
N. Greenland
Oxygen-18 in
a deep ice core
-45 -40 -35 -30 -25 ‰
c
ALLERØD
BØLLING
DENEKAMP
HENGELO
UPTON WARREN
BRØRUP
AMERS-
FOORT
TWO CREEKS
PLUM POINT
MOGADORE TILL
PORT TALBOT
BRADTVILLE TILL
ST. PIERRE
BECANCOUR TILL
WISCONSIN
GLACIATION
BEGINS
N. America
Glacier
retreat
b
Time
before
present
in 1000
years
New Guinea
Sea level
m
-100 -50 0
a
0 10 20 30 40 50 60 70 80 90 100 110 120 130

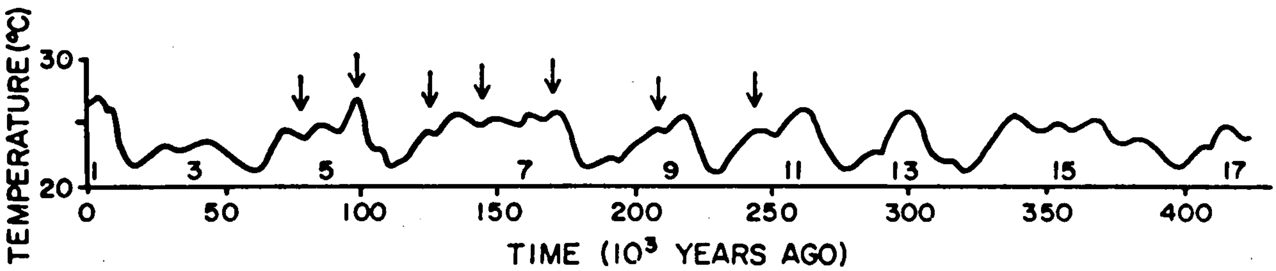


Figure 4. Generalized temperature curve for the surface water of the Central Caribbean, as derived from oxygen-isotope studies of deep-sea cores (Emiliani, 1966). Dating was carried out with the ^{14}C and $^{231}Pa/^{230}Th$ methods. Arrows indicate independently dated interglacial high sea levels (after Emiliani, 1969).

Figure 3. Climatic variations during the last 130.000 years, estimated by various methods (from Dansgaard *et al.*, 1971).

(a) Sea level changes on New Guinea (Veeh & Chappell, 1970);
(b) A ^{14}C dated stratigraphic study of Pleistocene deposits in the Ontario and Erie basins, showing the advances and retreats of the edge of the Laurentian ice sheet (Goldwaith *et al.*, 1965);
(c) The δ (^{18}O) variations in the Camp Century ice core (Dansgaard *et al.*, 1971);
(d) A ^{14}C dated pollen study from Holland (Van der Hammen *et al.*, 1967);
(e) An oxygen-isotope study of deep-sea cores showing part of the generalized temperature curve for the surface water of the central Caribbean (see fig. 4, after Emiliani, 1966);
(f) Northern hemisphere summer insolation curve (W. S. Broecker, 1968; cf. the curve for ϕ = + 45° in fig. 7).

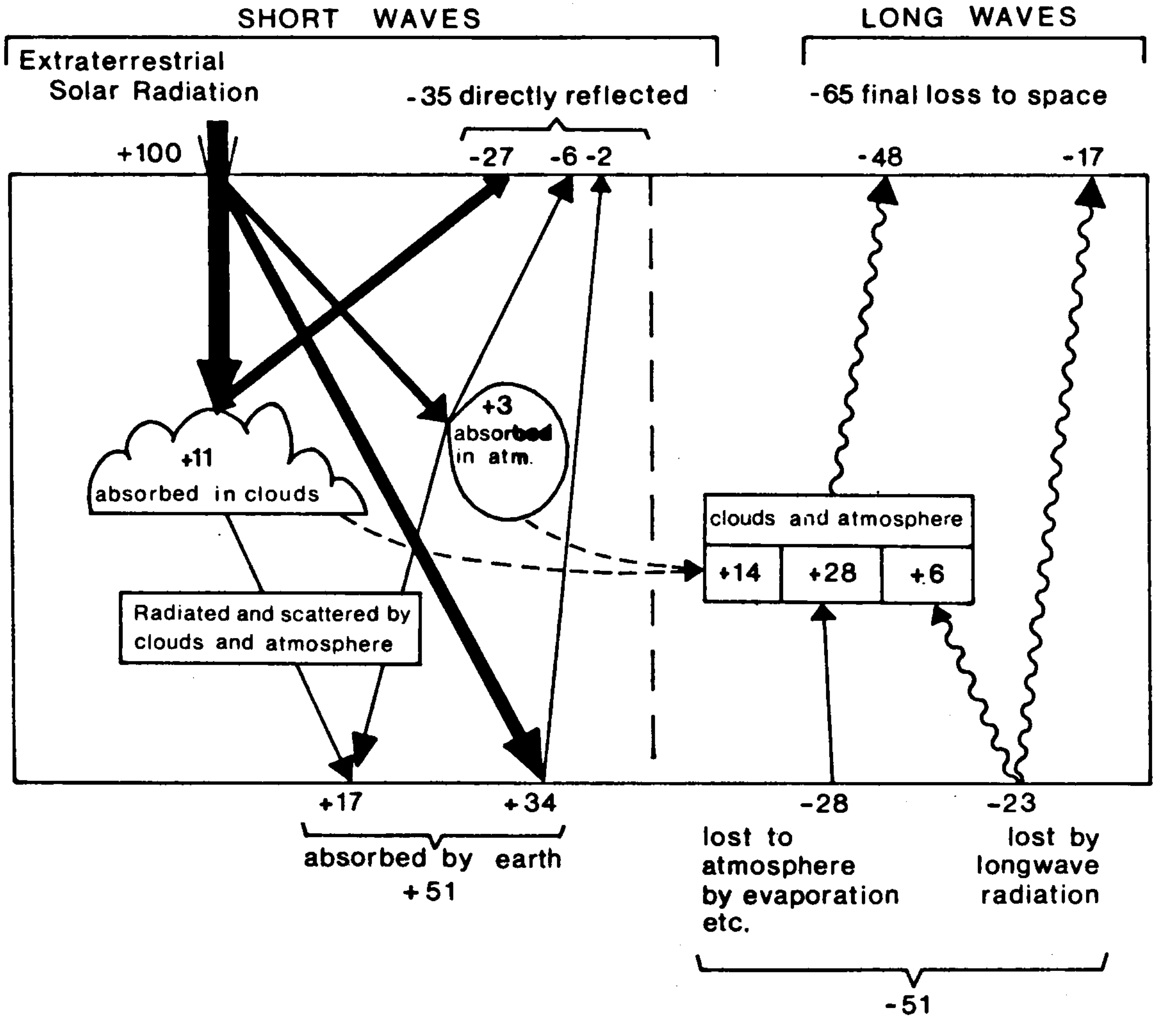


Figure 5. Average radiation balance of the Earth's atmosphere (after Möller, 1950, and Wexler, 1953).

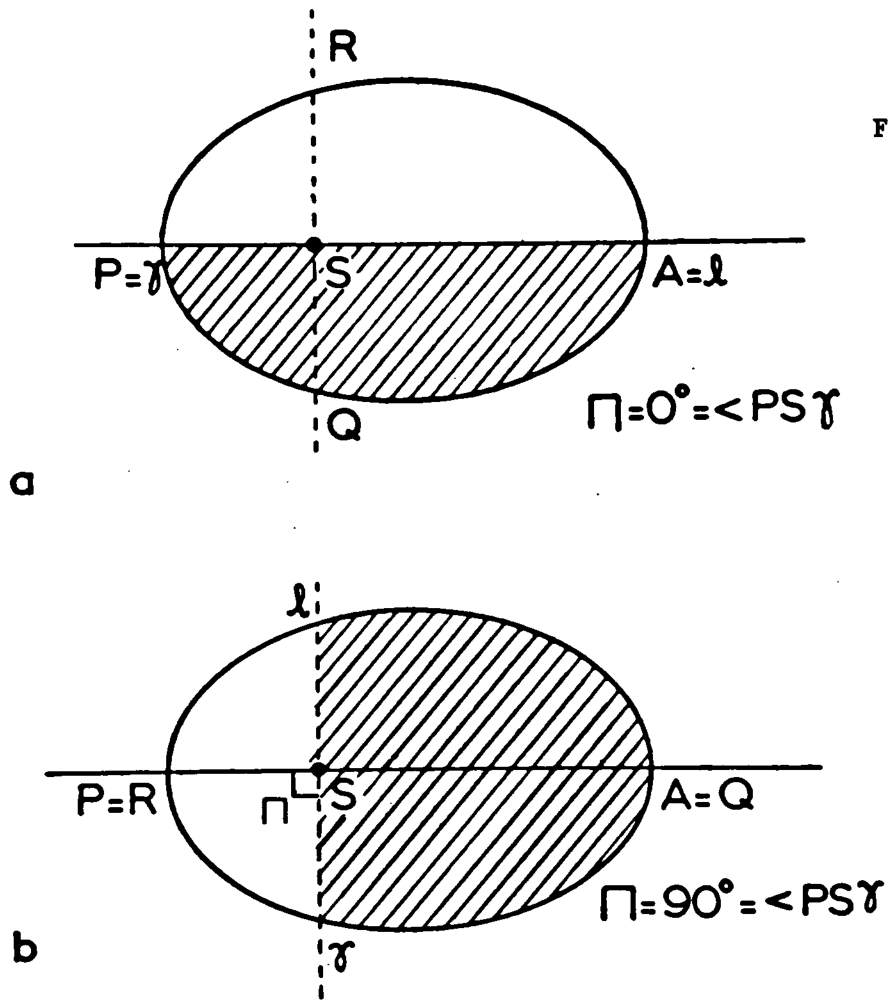


Figure 6. a) If the perihelion length $\Pi = PS\gamma = 0^o$, the Sun is in the equatorial plane when the earth is in the point P of its orbit. (γ is the equinox, S is the Sun). The Sun reaches its maximal angular height above the equatorial plane when the Earth is in the point Q (mid-summer), and is again in the equatorial plane when the Earth is in the point A (aphelion). Midwinter in the northern Hemisphere occurs if the Earth at the point R. Thus if $\Pi = 0^o$, the length of the summer (area PQA) is equal to the length of the winter (area ARP). The same occurs if $\Pi = 180^o$. In that case $A = \gamma$ and $P = \lambda$, while R and Q are interchanged.

b) If $\Pi = 90^o$, midsummer for the northern hemisphere occurs when the Earth is in the aphelion A and midwinter when it is in the perihelion P. Therefore, the northern summer (area $\gamma A\lambda$) will be long and cool, the winter short and mild. For the southern hemisphere the winter is long and cold, the summer short and hot. The situation for $\Pi = 270^o$ is just opposite to that for $\Pi = 90^o$. As a consequence of the precession and the proper motion of the perihelion the angle Π increase by 360^o in a time-interval of about 21.000 years.

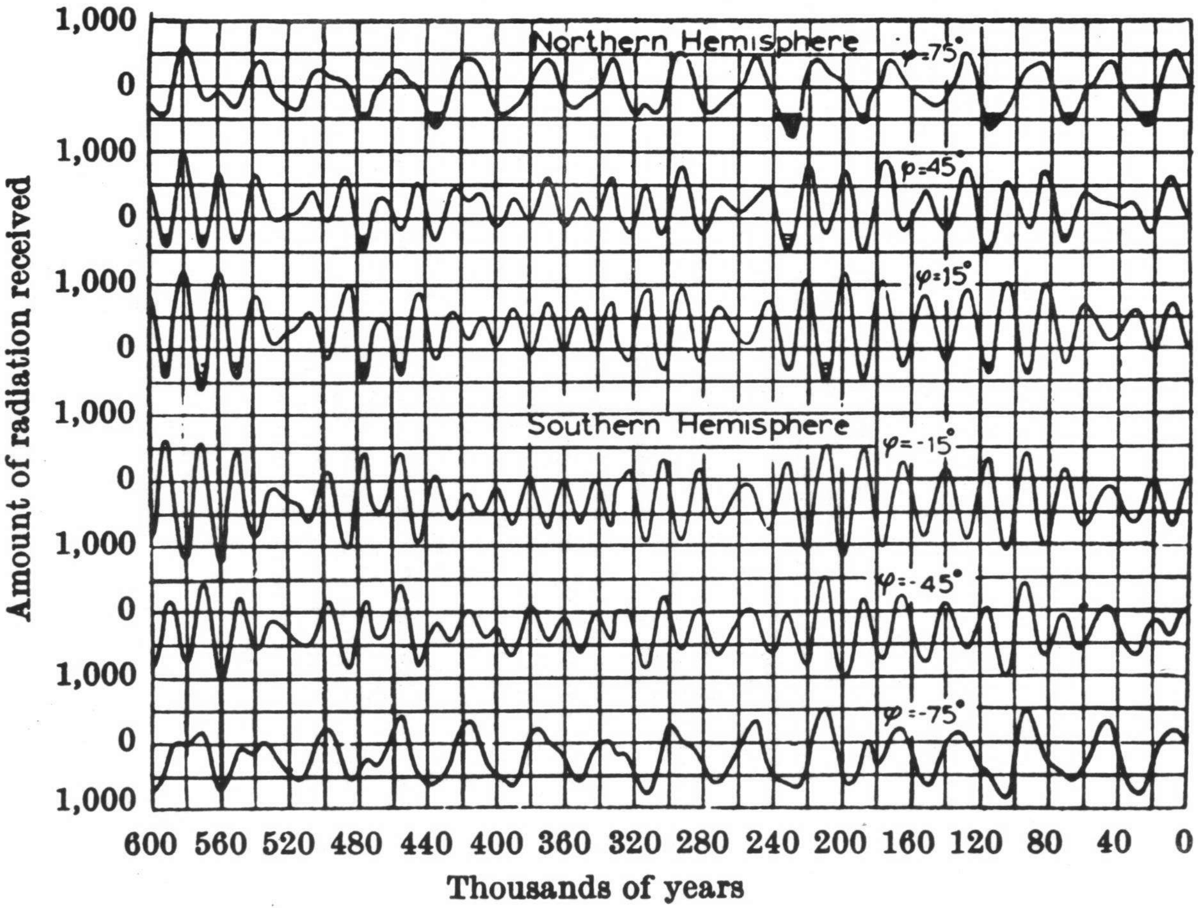


Figure 7. Milankovitch's (1941) insolation curves for the past 600.000 years. The figure represents the curves for geographical latitudes $\phi = \pm 15^o$, $\phi = \pm 45^o$, and $\phi = \pm 75^o$. Note that the curves for $\phi = + 15^o$ and $\phi = - 15^o$ show opposite variations; the amounts of radiation are given in "canonic units" (Milankovitch, 1941). The curves for $\phi = + 75^o$ and $\phi = - 75^o$ show maxima at about the same time. The curves for $| \phi | \leq 40^o$ are mainly regulated by the precession and show opposite variations in the two hemispheres.

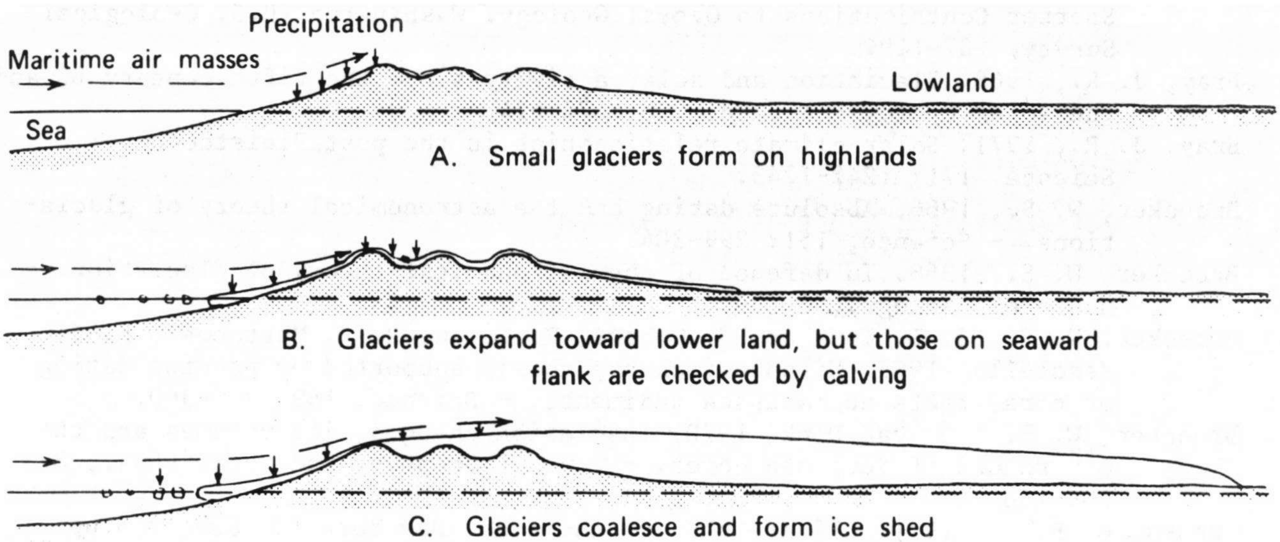


Figure 8. Idealized development of the Scandinavian ice sheet. Length of the section about 800 km. Not to scale (after Flint, 1971, p. 598).

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