The role of large-scale ice sheets in climatic history

Hermann Flohn
Universität Bonn
Meteorologisches Institut
Auf dem Hügel 20
D-5300 Bonn, FRG

ABSTRACT The climatic history of the earth contains two periods of some $10^7$ years length during which a continent in polar latitudes was partly or totally glaciated, while the opposite hemisphere was essentially ice-free. The present glaciation of Antarctica started about 38 Ma BP, preceding those of the northern continents by more than 30 Ma. The climatogenetic role of this hemispheric asymmetry will be outlined, as well as the role of variations in the composition of the atmosphere. Together with the varying land-sea distribution in polar latitudes, the latter primarily control the climatic history of the planet Earth.

Rôle des grandes calottes glaciaires dans l'histoire climatique

RESUME Dans l'histoire climatique de la Terre il y a eu deux périodes d'environ $10^7$ années au cours desquelles un continent à des latitudes polaires était partiellement ou totalement englacé, alors que l'hémisphère opposé était pratiquement libre de glaces. La glaciation actuelle de l'Antarctique a débuté il y a environ 38 Ma, précédant celles des continents de l'hémisphère nord de plus de 30 Ma. Le rôle climatique de cette dissymétrie entre les hémisphères sera souligné, ainsi que le rôle des variations de composition de l'atmosphère. Cette dernière, avec la distribution variable des terres et des mers aux latitudes polaires, contrôle en premier lieu l'histoire climatique de la planète Terre.

THE FIRST 99% OF EARTH'S HISTORY

During the history of the earth--i.e., since about 4500 Ma BP--several relatively long or short periods during which either one or both polar regions were glaciated alternated with other probably much longer periods, during which apparently no ice was found at either polar region. Kerner-Marilaun (1930) coined the term "acryogenic" for these periods, to distinguish them from the much shorter interglacial phases during the Pleistocene, when only the northern continents (except Greenland) were ice-free. The last acryogenic period lasted from the beginning of the Mesozoic until the early Tertiary, i.e., from about 225 until 38 Ma BP. The rapidly growing evidence for this, especially from the ocean bottom, has been reviewed by several authors, e.g., Frakes (1979), Kennett (1982) and Crowley (1983), taking into account the mobility of the earth's crust as evidenced by plate tectonics and paleomagnetic data.
Climatic history is an integral part of the Earth's history, even if our knowledge of the first 88% of the Earth's history is quite fragmentary. We know of a glaciation in the Huronian (Middle Precambrian, about 2300 Ma BP), spread over large parts of what is now North America, South Africa, and probably Australia and India. While the next 10^9 years were ice-free, there is convincing evidence that there were three, or perhaps four, large glaciations during the late Precambrian around 950, 750 and 650 Ma BP (Hambrey & Harland, 1985). Virtually all regions of the earth containing Precambrian rocks show some evidence of ice during this time, but not necessarily simultaneous. Strangely enough, paleomagnetic evidence suggests that many of these glaciations occurred in low latitudes: a fact that remains as yet obscure.

For the Phanerozoic era (i.e., during the last 570 Ma), our knowledge of climatic history is certainly better, but still far from complete. Evidence for a major ice sheet during the Ordovician (about 450 Ma BP) in north-central and western Africa—at that time near the South Pole—is well-known; there is also evidence for glaciation at this time from South Africa, Arabia, Europe, and North and South America. There is no evidence from the land masses that were then situated in the Northern Hemisphere, but most of the data were in low latitudes.

During the late Devonian (about 350 Ma BP), South America was partly glaciated. From the Late Carboniferous until the Late Permian, (i.e., from about 320 to 250 Ma BP), the main glacial centers moved in a complicated way through the former Gondwana continent, i.e., across South Africa and Antarctica towards the then coastal regions of Australia (Caputo & Crowell, 1985). This evidence indicates that during a considerable part of the Paleozoic, only the giant (about 60-70 x 10^6 km^2) Gondwana continent was partly glaciated, as the South Pole migrated through it.

In the Northern Hemisphere, where the continents were at least at one time connected with Gondwana into a single Pangaea, there is only one piece of evidence of glacio-marine deposits (in the Mid-Carboniferous) in what is now eastern Siberia (Chumakov, 1985). However, this seems to have been ephemeral. In other parts of the northern continents (North America, Europe, and China), coal deposits were formed in a moist, subtropical or tropical climate. Thus, during this long epoch, glaciation was essentially unipolar, limited to the Southern Hemisphere. This is a consequence of the path of the South Pole and needs no special interpretation, in contrast to the lengthy succeeding periods of the Mesozoic and Paleogene, when the pole position was not much different, but no ice existed at all. No definitive explanation can be given now for this phenomenon.

ICE FORMATION IN ANTARCTICA

During the transition from the Eocene to the Oligocene (38 Ma BP), a sudden cooling occurred at the ocean bottom around Antarctica, as well as along the west coast of North America and Alaska ("sudden" means here over a period of not more than 10^5 years). This terminal Eocene event (Kennett, 1982) coincided with the beginning of occasional appearance of ice-rafted material in the southern oceans and with a change in vegetation along one of the Antarctic coasts. Snow and ice, probably in the form of "warm", fast-moving glaciers in elevated terrains, were clearly present in Antarctica after 25 Ma BP, but not before the Mid-Miocene (15-14 Ma BP) do we have unequivocal evidence for a complete glaciation of the East Antarctic continent (nearly 90% of the present area), together with other signs of a dramatic change of atmospheric/oceanic circulation and climate, at least in the Southern Hemisphere (cf. Denton et al., 1984). Vincent & Berger (1984) have correlated this cooling event with a preceding carbon isotope (δ¹³C) excursion, during which much organic carbon was extracted and deposited at the ocean shelf areas. Here a high correlation between δ¹⁸O (representing temperature) and δ¹³C (representing atmospheric CO₂ content) has been observed. It should be noted, however, that these deposits, which indicate a cool period with strong atmospheric circulation, are found along Northern Hemisphere coasts.
The role of large-scale ice sheets

Higher bioproductivity of equatorial and coastal upwelling regions, as well as powerful deep ocean currents that erode the ocean bottom and create breaks in the sedimentary record, accompany intensification of the atmospheric circulation, which is driven (according to the well-known Bjerknes circulation theorem) by the (isobaric) temperature difference between equator and pole, an indicator of the baroclinicity of the atmosphere (Kennett, 1982). This fundamental parameter increased (at the ocean surface) from about 10°K during the Mesozoic to at least 27–28°K now (disregarding polar ice).

After the final establishment of the East Antarctic Ice Sheet 14 Ma BP—most probably with a smaller volume than now—circulation in the atmosphere and ocean intensified strongly in the Southern Hemisphere. The climatic zonation of a continent such as Africa (at that time about 6° further south than today) was not much different from the current configuration: an equatorial rain forest, tropical summer rain belts on both flanks, the arid zones probably less dry than now. It is impossible to be more detailed. The intensification of the wind-driven circulation, together with the cooling of the surface waters in contact with the glaciated continent, led to an intensification of upwelling along the Benguela coast and to the hyperaridity of the coastal regions (van Zinderen Bakker & Mercer, 1986), and established during a cold/dry episode around 10-9 Ma BP. After this a warming occurred, especially well developed north of the equator, e.g., in Ethiopia, while no upwelling occurred along the northwest coast of Africa.

During the terminal part of the Miocene (Messinian epoch, 6.5-5.2 Ma BP) a general cooling, together with a growth of the Antarctic Ice Sheet, occurred. The ice sheet expanded rapidly into West Antarctica; simultaneously, the mountains of southern South America became glaciated. The Antarctic ice apparently had become cold and slowly moving, with a tendency for a positive mass balance; this, together with Milankovitch-type oscillations and glacioeustatic sea-level fluctuations up to 70 m, led to the repeated closing and opening of the Mediterranean, together with the famous “salinity crisis” affecting the adjacent continents. A very comprehensive sequence of paleoclimatic events in the Black Sea and Ukraine, from about 7.3 Ma BP onwards, has been described by Borzenkova & Zubakov (1985), together with the gradual cooling, which apparently affected the whole globe until the mid-Pleistocene. Along the northwest coast of Africa, Stein & Sarnthein (1984) reported no evidence of increased oceanic fertility, which indicates no distinct coastal upwelling as correlated with increasing circulation at the Northern Hemisphere. During this time the Antarctic ice volume was probably 50% larger than now (estimated from data of Kennett (1982)).

GLACIATION OF THE NORTHERN CONTINENTS

The last-mentioned global cooling did not immediately lead to a glaciation of the northern continents except for isolated mountainous regions in Alaska (Shackleton et al., 1984). In contrast to Antarctica, the northern land masses did not extend into the immediate vicinity of the pole. Therefore, glacial centers developed later in the belt 60–70°N (Greenland, Baffin Island/Labrador, then (probably last) Scandinavia). However, recent results from the bottom of the central Arctic Ocean and its Atlantic margins (Thiede, 1986) revealed some contradictory facts indicating short periods with sea ice as early as the latest Miocene.

The timing of the onset of this glaciation in the Northern Hemisphere is the subject of some controversy. It now seems to be well established that the early Pleistocene (about 5-3.5 Ma BP) was a time of relative warmth (Fig. 1), during which the West Antarctic ice sheet partly degraded. Only after the end of this period did the fluctuations in the global ice volume become larger, as revealed in the ocean bottom sediments, simultaneously with a cooling of the Bogotá high plateau (Hooghiemstra, 1984) and a glaciation of other parts of the Andes. Even more marked all over the globe was a strong cooling 2.5 Ma BP, which generally initiated the
glaciation of the northern continents including Iceland. Evidence for such a two-step cooling has been presented, during the last years, to such an extent that further skepticism is no longer justified. We quote here only the work of 17 authors on a deep-sea drilling core near the Rockall Bank (56°N, 23°W) (Shackleton et al., 1984), together with Prell (1984), who studied a series of cores from tropical regions, and Stein & Sarthein (1984), who investigated sediments from the tropical Atlantic. By 2.5 Ma BP, sea ice covered the Arctic Ocean, though at first only seasonally, with long ice-free intervals (Herman & Hopkins, 1980). Only relatively late—perhaps not before the Matuyama-Brunhes boundary 0.7 Ma BP—did a permanent marine ice cover develop which could, in the central Arctic region, survive all warm interglacials (such as today).

\[ \Delta T \text{ Pliocene(Opt.) - recent} \]

\[ \begin{align*}
\text{Wi} & \quad 12 \\
\text{Year} & \quad 10 \\
\text{Su} & \quad 8 \\
\end{align*} \]

**FIG. 1** Temperature difference (\(\Delta T\)) between the Early Pliocene Optimum (about 4.6-3.5 Ma BP) and the present, zonally averaged (after Borzenkova & Zubakov (1985), Table 3).

This history is interesting in itself, but it has important consequences for both the overall history and our understanding of climate (Flohn, 1980, 1983). First of all, it reveals a surprisingly large degree of independence of the climatic patterns in the Northern and Southern Hemispheres: a hitherto neglected consequence of the coexistence (at least since the early Miocene) of a truly polar continent isolated by a large circum-Antarctic ocean and a nearly land-locked (now about 85%) Arctic Ocean, the two having fundamentally different heat and radiation budgets. From the geophysical point of view, this independence is quite understandable. Following V. Bjerknes’ classical theorem, the circulation of an atmosphere (or fluid) on a rotating planet depends on the number of isobaric/isothermal solenoid—equivalent to the thermal gradient on an isobaric surface—and the speed of rotation. These two quantities are combined in the well-known "thermal Rossby number" \(\text{Ro}_T\), expressed as the ratio between the thermal wind \(\partial \psi / \partial x\) as maintained by the horizontal (latitudinal) temperature difference \(\partial T / \partial \psi\), and the angular momentum of the solid earth, i.e., its rotation speed. Assuming this to be constant—and indeed the rotational speed of the earth varies from year to year by only a few milliseconds, i.e., a factor of about \(10^{-10}\)—the atmospheric circulation depends only on the thermal wind, i.e., on the equator-to-pole temperature difference averaged over, say, the troposphere up to 300 or 200 hPa, equivalent to an elevation of 9 or 12 km. Any difference in this parameter between the two hemispheres causes an asymmetric circulation pattern.
The role of large-scale ice sheets

The second major feature of this climatic history is the striking coexistence of a glaciated East Antarctic continent and an ice-free Arctic Ocean during a period of more than 10 Ma. This asymmetric, unipolar glaciation lasted much longer than the whole Pleistocene (1.6 Ma) and the latest Pliocene with its cyclic occurrence of about 20-25 glacial and interglacial. This must have led to an even greater asymmetry of the planetary climatic zonation than now. This leads to the important question (to which we shall return): what would be the pattern of climatic zones on such an asymmetric globe? Answering this is (or at least should be) a fascinating aspect of designing a climate model.

PHYSICAL ASPECTS OF CLIMATIC EVOLUTIONS: THE ROLE OF ICE SHEETS

Climatic models have been applied to the acryogenic climate of the Mesozoic, which peaked during the Mid-Cretaceous (about 100 Ma BP). Barron & Washington (1984) have indicated that an ice-free polar climate--given the land-sea distribution of the Cretaceous--could not have existed with the present composition of the atmosphere, and postulated that the CO$_2$ content was 2-10 times higher than it is today. Flannery et al. (1984) used an energy balance model and came to the conclusion that a CO$_2$ increase by a factor 10-15 would be necessary to maintain the Cretaceous climate. This coincides with an estimate by Budyko (1982) and Ronov (quoted after Budyko), who assumed that the rate of deposition of carbon mass in sediments per unit of time is proportional to the atmospheric CO$_2$ content, and thus concluded that the concentration of CO$_2$ in the atmosphere was 1000-4000 ppm during most of the Phanerozoic. Using a more complex geochemical model, Lasaga et al. (1984) came to the conclusion that the atmospheric CO$_2$ content during the Cretaceous was about 13 times as high as now; during the Eocene this factor was 3. This conclusion, however, is controversial (cf. Shackleton, 1984).

It remains to be explained why during the Carboniferous and Permian such large portions of the globe were glaciated at the same time as the largest known coal deposits in the Northern Hemisphere were forming, most probably in equilibrium with a high CO$_2$ level of the atmosphere. Note that after the last glaciation, about 13 ka BP, the re-expansion of tropical forests nearly coincided with an increase in atmospheric CO$_2$ content.

Fluctuations of the equator-to-pole temperature gradient are the consequence of the occurrence (or absence) of ice (continental or marine) at the poles, while the temperature of the equatorial oceans is controlled by the available solar radiation, which must be sufficient to evaporate water and to maintain a convective equilibrium in the atmosphere, with a relative humidity near 78%. This gives an upper limit to the sea surface temperature (SST) on the open ocean, which reaches now 30°C (Newell & Dopplick, 1979). However, this value might vary if the composition of the atmosphere or the "solar constant" were different. The available SST data from the equatorial Pacific, Atlantic and Indian Oceans invariably show a rise of 0.6-0.7°C between about 1900 and 1980, which is consistent with the observed increase of "greenhouse" gases such as CO$_2$.

As pointed out earlier (Flohn, 1978), the physical reasons for the climatic differences between the glaciated Antarctic continent and the glacio-marine Arctic Ocean must be seen in their different heat and radiation budgets. The net radiation loss at the Antarctic surface is about 5 times greater than at that of the Arctic because in the Arctic, evaporation through the leads and polynyas cause a quite effective long-wave counter-radiation of the atmosphere down to the surface. Furthermore, the advection of relatively warm air from the oceans leads much more heat and water vapor into the central part of the Arctic than into the Antarctic, where the zonal component of the circulation is much stronger than the meridional exchange caused by both stationary and migrating eddies. Unfortunately, no up-to-date comparative data are available.
At any rate, the present climatic differences are surprisingly high (Table 1), especially in the troposphere (the layer equivalent to 3-9 km elevation). If one compares the average tropospheric temperature at the poles (denoted $T_N$ and $T_S$ for the north and south poles, respectively) to that of the equator (denoted $T_E$), the seasonal variations between the equator-pole differences, shown in Table 1, are even more striking (Flohn, 1978).

**TABLE 1 Differences in tropospheric temperature between equator and poles**

<table>
<thead>
<tr>
<th></th>
<th>$T_E - T_N (^\circ C)$</th>
<th>$T_E - T_S (^\circ C)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>32.9</td>
<td>29.7</td>
</tr>
<tr>
<td>July</td>
<td>17.3</td>
<td>44.1</td>
</tr>
<tr>
<td>Year</td>
<td>27.3</td>
<td>39.1</td>
</tr>
</tbody>
</table>

Remembering the importance of the temperature differences for the intensity of the thermally driven atmospheric circulation, and neglecting the stratosphere, the annually averaged circulation in the Southern Hemisphere is more than 40% stronger than in the Northern Hemisphere. During July the difference is a factor of more than 150%, while during December-February there is little difference between the strengths of the circulation in the two hemispheres. The different heat budgets of the two polar regions create a marked hemispheric asymmetry, which frequently has been neglected in designing climatic models.

Figure 2 demonstrates the observed seasonal march of the position of the subtropical anticyclones (STA) as a function of the tropospheric temperature gradient in the two hemispheres. With increasing gradient the STA migrates towards the equator, and the expanded polar vortices with westerly winds intensify.

Without a model, the corresponding figures during the even more asymmetric Pliocene or the (probably symmetric) Cretaceous can only be guessed. This is due to the unknown role of the surface inversion now more or less permanently formed over both polar regions. This inversion is rather weak during summer, but very strong during winter, and much stronger above the Antarctic and Greenland ice than above the Arctic drift-ice, where a continuous flux of sensible and latent heat from the unfrozen sea across the leads and polynyas, and even across the ice floes, reaches the atmosphere.

PHYSICAL ASPECTS OF CLIMATIC EVOLUTION: ATMOSPHERIC COMPOSITION

Recent modelling investigations have indicated, as shown above, that the climate on an ice-free earth, such as during the Cretaceous, can only be understood by assuming a much higher CO$_2$ concentration in the atmosphere than at present. In Flannery's model—when taking into account the constraint of tropical evaporation (Newell & Dopplick, 1979)—a realistic palaeo-temperature pattern can only be achieved with an approximately ten-fold increase in the CO$_2$ content of the atmosphere.

For the early Pliocene, which may have been a period of climatic evolution after a prolonged CO$_2$ induced warming (Flohn, 1983), model experiments have not yet been done. Likewise, reliable palaeoclimatic data from the central Arctic Ocean are not yet available. If we follow the well-founded argument of Shackleton (1984) and other authors, the existence of a permanent drift-ice cover over the Arctic Ocean can be excluded for this period. A seasonal ice-cover, however, cannot be excluded (Herman & Hopkins, 1980), certainly not for a broad belt along the coasts. In the central Arctic, a weak winter inversion may have existed; during summer, SST's around 8°C seem to be most likely. Since the equatorial belt cannot have been
The role of large-scale ice sheets

FIG. 2 Seasonal migrations of the latitude (φ) of the subtropical anticyclones (STA) in the Northern (NH) and Southern (SH) Hemispheres as a function of the equator-pole temperature difference (T_E–T_P) in the layer at pressures in the range 300-700 hPa.

much warmer (by 1.5°C; see Fig. 1), T_E–T_N should have been only slightly lower than the present 300-700 hPa value (which excludes each surface inversion above the ocean). During winter, the temperature could indeed be substantially higher (by about 10°C); this could yield for the annual average of T_E–T_N c. 20°C. Borzenkova & Zubakov (1985) cite, for the sub-Antarctic ocean, higher temperatures as well; we may estimate a value of 5–7°C greater. The annual average of T_E–T_S might therefore have been reduced, during the Pliocene optimum, to 32–35°C. Thus we estimate the asymmetry of the circulation-producing thermal difference to have been slightly higher than now.

For this general warming during the Pliocene climatic optimum, Budyko (1982) has proposed a CO_2-level near 600 ppm; a verification of this estimate is certainly needed. The warming at both polar zones, including the sub-Antarctic, indeed argues for a different composition of the atmosphere than now. However, here we have to take into account not only CO_2 and CH_4 (which are included in Flannery’s model) but also water vapor due to the higher SST’s that also exist in the tropical belt.

Climatic consequences of today’s hemispheric asymmetry are well-known. Some examples are:

a) the different positions of the major climatic belts, e.g., the position of the subtropical anticyclonic belts (Fig. 2).
b) the encroachment of the stronger Southern Hemisphere circulation on the Northern Hemisphere, except during northern winter; this results in an annual average position of the equatorial trough (the Intertropical Convergence Zone) at Lat. 6°N.

c) the occurrence of a weak and irregular equatorial counter-current in both the Atlantic and the Pacific Oceans north of the equator (Lat. 4°–8°N, Fig. 3), together with a seasonal upwelling zone in both oceans at Lat. 0°–5°S.

![Average Temperatures (°C) at a depth of 300 ft = 91 m, at longitude 140°W](image)

**FIG. 3** Seasonal variations of the temperature at 91 m depth along Long. 140°W (time-latitude section). Data after Robinson (1976).

The climatic asymmetry due to the unipolar glaciation during the early Pliocene (5-3 Ma BP) must have been somewhat greater than now. According to the aforementioned model results for the Cretaceous, and those under actual conditions, it seems unlikely that the marked hemispheric contrast during this time—especially the temperate climate in high northern latitudes—could have happened without an atmosphere with higher CO₂ concentration. Likewise, the H₂O content of the atmosphere should have been somewhat higher, although no figures can be given. Since no results of comprehensive interactive models which take fully into account heat storage and dynamics of the oceans, are yet available, any estimate of the "effective" CO₂ content of the atmosphere that could maintain such a strange climate could not be more than a guess.

Two important climatogenetic boundary conditions during early Pliocene should also be mentioned:

a) closure of the Panama land bridge, which blocked the great westward equatorial ocean current and forced the warm water from the tropical Atlantic northward to intensify the Gulf Stream;

b) uplift of the Tibetan Plateau and adjacent mountains, which intensified the summer time monsoon system over Southern Asia and Africa (low-level W-SW winds, high-tropospheric easterly jet), leading to a marked dessication of the Sahara, Arabia and Indo-Pakistan up to Long. 73°E (Flohn, 1985).
CONCLUSIONS

Looking back at the long-term climatic history of the earth, acryogenic climates alternate with periods of unipolar and bipolar glaciations. Because the Antarctic ice sheet is now smaller than during the late Miocene (Denton, 1984) and because the northern continents were covered during many glaciations—including the last one 18 ka BP—by up to $32 \times 10^6$ km$^3$ of ice, today's climate can only be defined as a weak residue of a bipolar glaciation. In addition to the other known climatogenetic effects with different time scales—such as land-sea distribution and topography, orbital variations and volcanism—the composition of the atmosphere plays a greater role than hitherto assumed (Barron, 1985). Short-period variations on the scale of $10^2$-$10^3$ years contribute substantially and are able to initiate rather abrupt changes.

Changes in the atmosphere's composition—notably CO$_2$ and H$_2$O—are caused primarily by exchange processes between ocean, atmosphere and biosphere. During recent years, several authors (e.g., Schnitker, 1980; Sancetta & Silvestri, 1986) have pointed out the ability of different circulation modes in the abyssal ocean to undergo rather rapid changes as a possible main cause of "abrupt" climatic fluctuations at the $10^2$-$10^3$ year scale. Waxing and waning of the subpolar continental ice-sheets occur on the time scale of $10^4$ years, obviously related to orbital variations (Imbrie et al., 1984). Waxing and waning of the polar continental ice sheets, however, occurs on the $10^5$-$10^6$ year time scale, apparently as a consequence of changes in land-sea distribution (i.e., plate tectonics) and atmospheric composition.

Since they are controlling the baroclinicity of the atmosphere, these two geophysical effects are primarily responsible for long-period climatic changes at the earth. Due to the recent investigations of Oeschger et al. (1983), Lorius et al. (1985), Shackleton (1984) and others, we are able to reconstruct the past fluctuations of CO$_2$ and other "greenhouse gases", which appear to have been promoted to one of the most efficient climate-producing factors at all time scales.

REFERENCES


The role of large-scale ice sheets


