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The history of the Antarctic climates over 'geologic' time-scales*

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Timing of the long-term tectonic effect on climate evolution has been random over the last 10^9 years, and has operated by altering the latitudinal distribution of land and sea, by affecting the level of the sea and the importance of ocean currents, and by contributing to orographic and continentality effects. Among the detected cycles in climate, the longest appears to have a period of about 10^5 years. This has been a major cycle over the last 10^6 years but it is not recognised definitely in older rocks. Because only short geologic records have been studied, the prominent and important 10^5 year cycle cannot be correlated certainly with the Milankovitch parameters (particularly not with eccentricity of the orbit). The 4 x 10^4 year obliquity cycle appears to be the most significant among recognised cycles, owing to its simultaneous effects in both hemispheres and to its known influence on ice growth through effects on high-latitude summer temperatures. Precession cycles of 2 x 10^4 years are clearly recognised in the geologic record. The cause of the 10^5 year cycle presently is unknown and causes are being sought in geophysical models of upper mantle stressing and relaxation in response to ice loading and melting.

Introduction

Geologists have long known that variability in climate comprises variations operating over a range of time-scales. A given climate change may thus reflect any of several causes which fluctuate over periods from several years to 10^5 years or possibly longer. Some changes do not belong to any systematic oscillation; that is, they are the result of some non-reversing alteration in the earth-atmosphere system which governs climate. The variability of climatic elements throughout geologic time therefore is a function of all factors, periodic and aperiodic, which control climate. This gives rise to a compound curve of change, representing many superimposed trends and consequences arising from 'one-off' events. Interpretation of such curves involves detailed study of individual cycles and events as seen in variability of geological materials, as well as theoretical considerations of important known phenomena, as for example orbital cyclicities, and the closing of the Isthmus of Panama about 3 x 10^6 years ago. It is only when all such cycles and events are known, and their timing verified, that the composite curve of climate change can be fully dismembered into its components.

An effort will be made here to identify factors which have influenced the evolution of Antarctic climate over the last 10^9 years. The best known of these are discernible in the geologic record of the relatively recent past; the effects of events or cycles which operated in more remote times are less obvious because the record is less complete. Also, a special constraint on interpretation of Antarctic climates arises from a scarcity of geologic materials, owing to the fact that Antarctic rocks are predominantly inaccessible beneath the ice cover. More than for most parts of the globe, the strength of conclusions is lessened by the fact that Antarctic climates must be largely inferred from extrapolation of what is known of global climates.

The major cycles thought to affect earth climates are as follows:

(i) a proposed cycle related to the length of the cosmic year and to the position of the solar system relative to the Magellanic clouds (period between ~1.5 and 5 x 10^8 years);

(ii) cyclicity in the eccentricity of earth's orbit around the sun (period ~9.3 x 10^4 years);

(iii) cyclicity in the precession of the equinoxes (period ~2.1 x 10^4 years);

(iv) cyclicity in the obliquity of the ecliptic of the earth (period ~4.1 x 10^4 years). This cycle is very significant for high latitude zones, including Antarctica and, through affecting global albedo by growth of ice there, may be the forcing function for recent global changes.

Geologic or atmospheric events which may have contributed to variations in earth climate over geologic time, are often difficult to identify and

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most are subjects for controversy. Geologic events involve either vertical or horizontal movements of parts of the earth's crust. These tectonic movements assume importance in that they alter oceanic and, to lesser effect, atmospheric circulation; they have caused large variations in global albedo by giving rise to changes in the level of the sea and in the latitudinal distribution of both land and sea; and they enhance or diminish continentality effects through the joining together or sundering of continental blocks. There may be in addition non-tectonic events of significance in climatic change and variability. These include possible changes in the composition of the atmosphere, such as in levels of CO_2 concentration, and possible though unproven variations in solar insolation over geologic time.

Individual cycles and events, of proven or suspected occurrence, will be described in the following section.

History of Antarctic climate

There is some small probability that a major change in the earth's obliquity took place about 5.5 to 6.0 x 10^8 years ago and that this would have affected Antarctica as indeed the entire globe. All major glaciations on earth after this time took place in relatively high latitudes, while palaeomagnetic measurements suggest that the two major glaciations of earlier times were sited in low to middle latitudes (Frakes 1979). The latter case is explainable on the basis of decreased insolation in the tropics and increased polar insolation during times when the tilt of the earth's axis was greater (Williams 1975). Evidence has not yet been discovered that either of the early glaciations occurred on Antarctica, although it was positioned in similar latitudes to continents known to have been glaciated. Antarctica thus may have been glaciated at about 2.3 x 10^9 and again within the interval 9.0 to 6.0 x 10^8 years ago; if so, the present ice sheet conceals the evidence.

Two later glaciations, subsequent to a possible change of obliquity to near the present value, are recorded in the Antarctic rock record, though the climates of intervening times are poorly known. The first was the widespread glaciation of Gondwanaland which took place in the latter part of the Palaeozoic Era (3.2 to 2.5 x 10^8 years ago); the second apparently was initiated about 2.6 x 10^7 years ago and continues to the present. In both cases, the glaciated landmasses occupied high latitude positions, although in the second, Antarctica had been separated from formerly adjacent continents by continental drift. In the time between these late glaciations it appears that Antarctica was not glaciated and instead harboured abundant vegetation, now seen as deposits of coal (~2.2 x 10^8 years old) and accumulations of spores and pollen which date to between about 1.0 x 10^8 and 2.0 x 10^7 years old.

Although the two earliest of these four glaciations are not known from Antarctica, their occurrence elsewhere has been used to suggest a cyclicity of global cooling related to the length of the cosmic year (Williams 1972, 1975; Steiner and Grillmair 1973). If the half-cycle of Williams is applied (period — ~1.55 x 10^8 years), a few predicted glaciations are not known to have occurred on Antarctica or elsewhere (e.g. at 1.55 x 10^9, at 1.25 x 10^9, and at 1.55 x 10^8 years ago), and this tends to weaken the value of the hypothesis of cyclicity. Also one major glaciation of the northern hemisphere (~4.0 x 10^8 years ago) does not fit the cycle. Thus, there does not appear to be strong evidence for cyclicity based on the cosmic year, although some known times of glaciation coincide approximately with those predicted by the model.

The timing of the advent of the current glaciation of Antarctica unfortunately is not known. It has recently been determined that fluctuations in sea level comparable in magnitude to those caused by comparatively recent fluctuations in Antarctic ice volume, occurred throughout the last 5.0 x 10^8 years (Vail et al. 1977; Vail and Hardenbol 1979). However, in all such considerations, similar large fluctuations might be due to tectonic movements. If these sea level changes do indeed reflect glacial-eustatic events solely, with no tectonic input, ice has been present on Antarctica for much of the last 5.0 x 10^8 years. However, definite evidence of the most recent glaciation extends back only to about 2.6 x 10^7 years. This constitutes a major problem in Antarctic climatic history, as the Antarctic continent is known to have occupied a polar or near-polar position for the last 3.2 x 10^8 years. First, if in a zone of low insolation for this long interval, why was Antarctica only intermittently glaciated? And second, why did ice sheets develop only at two times (between 3.2 and 2.5 x 10^8, and at about 2.6 x 10^7 years ago)? To the first question there is as yet no answer, other than the fact that on geologic evidence the entire globe clearly was very warm over much of this time (Frakes 1979). Geologists have sought and found explanations for the initiation of both glaciations in major tectonic events, synchronous with climatic changes and of enormous consequence for global climate, though in many cases geographically far removed from Antarctica. The vastly different and variable distribution of land and sea ensures that absorption, distribution and transport of heat energy will have been greatly different than at present (Frakes and Kemp 1973; Frakes 1979; Schnitker 1980; Barron et al. 1980; Thompson and Barron in press).

From the end of the Late Palaeozoic glaciation (~2.5 x 10^8 years ago) until the end of the Eocene epoch (~3.7 x 10^7 years ago), the world oceans were characterised by low thermal gradients, warm waters extending to high latitudes, and sluggish circulation. Contributing to this was a large concentration of highly heat absorbing oceans in the tropical zones. Near the end of this interval, continental fragmentation opened the Atlantic Ocean, and the southern polar oceans (south Indian and Weddell Sea regions) became dominant sources of cold water, thus increasing the tempo of vertical circulation in the oceans. The tempo was further enhanced with the deepening of the shallow seaway between Australia and Antarctica, and the consequent draining of cold water from the south Indian into the South Pacific gyre system, which in effect isolated Antarctica and cooled its surface.

Increased vertical circulation in the oceans is taken to be the forcing factor in the most recent glaciation and for this to happen tectonic events were required to open the Arctic seas as a further source of cold water. This took place in middle Miocene time (~14 x 10^6 years ago) and as a consequence the ancestral North Atlantic Deep Water was formed. However, in its early stages NADW was relatively warm (as now) and in upwelling around Antarctica after the Atlantic passage, it provided the prime evaporative source for construction of the Antarctic ice sheet. From studies of stable isotopes in marine sediments the large build-up is known to have begun about 14 x 10^6 years ago (Shackleton and Kennett 1975; Shackleton and Opdyke 1977). The modern scheme of oceanic circulation was essentially established with the closing of the Isthmus of Panama about 3 x 10^6 years ago.

It is assumed that growth of ice sheets in Antarctica led to establishment of steeper temperature gradients in the atmosphere as well as in the oceans in the interval from about 14 x 10^6 to 3 x 10^6 years ago. By the end of this period, the resulting increase in global albedo led in turn to growth of the massive late Cenozoic ice sheets of the northern hemisphere, although earlier (~15 x 10^6 years ago) large mountain glaciers existed in coastal Alaska. Since then, the earth has undergone several reversals of climate, culminating over the last 8 x 10^5 years in a major cyclicity having a period of about 10^5 years. The latter cycles are detectable in ice cores from Antarctica and in marine sediments from around the continent.

Meteorologists and quantitative climatologists no doubt will be disappointed in the qualitative nature of these scenarios and that they rest on infirm physical bases. Geologists, on the other hand, will be disappointed if others do not recognise the special nature of their problem. The world was vastly different in its configuration from what it is now, and only the most basic of climatological premises can be applied. Further, evidence about evolving configurations is only piecemeal. There is hope, however, in that energy-balance and general circulation models are now being applied to some of the problems (e.g., Manabe and Hahn 1977; Thompson and Barron in press).

Cyclicity in climatic change

As is apparent from the foregoing, there is no evidence of any obvious cyclicity to Antarctic climate over periods longer than 10^5 years. Rather, variation in climate over most of earth history appears to be governed by tectonic events which are randomly spaced in time. These are fairly well documented for the last 10^8 years but less so for earlier times. In reasoning thus, however, it is important to keep in mind that the resolving power of radiometric dating techniques is less for older than younger rocks; that is, the common ± 5 per cent errors of the method give rise to progressively greater uncertainties in dating old rocks, and most significantly, these therefore prevent dating of any short wave-length cycles which may be found to exist. This situation is made worse by the fact that materials to which dating techniques can be applied are not abundant in the rock record; palaeontological dating of rocks suffers from similar limitations. To sum up: climatic cycles with periodicities greater than about 10^5 years are not established for the time before about 10^6 years ago. Obvious rock cycles are known to exist but most are not closely dated and, at any rate, their relationships to possible climate variations are not definitely established.

In marine sediments from around Antarctica there is strong evidence of cyclic climate change over the last 7 x 10^5 years (Frakes 1978, 1979 Fig. 8-6). Seafloor carbonate proportions vary, as a result of variations in biologic productivity and/or carbonate dissolution, both of which may be due to temperature changes in the water column, and in such a way as to suggest cycles of about 10^5 years wavelength. These are mimicked by variations in diversity of surface microfauna (Keany and Kennett 1972), which is taken to be a measure of ocean temperature, and by other oceanic temperature and/or ice volume records from distant regions (e.g. Van Donk 1976; oxygen isotopes, equatorial Atlantic). By application of biogeographic factors to the oxygen-isotope curve for the last 5 x 10^5 years, Hays et al. (1976) derived a summer temperature curve for the subantarctic Indian Ocean, to which they then applied spectral analysis. The study indicated that some 50 per cent of total variation in the curve is accounted for in the spectral peak corresponding to the period of variation in eccentricity of the earth's orbit (~9.3 x 10^4 years). At this stage, it is best to remember that the temperature/ice volume curves are realities — that is, climate was indeed varying over a cycle of some 10^5 years — but that the forcing function has not yet been positively identified.

Two studies have now shown that direct connections between the climate curve and the eccentricity cycle are doubtful (Rooth et al. 1978; Kominz et al. 1979). The first paper cites the fact that calculated values for some eccentricity minima and maxima do not differ greatly, while isotope amplitude remains constant. The second paper detects cross-spectral peaks which are at least 8 to 20 000 years removed from both isotope and eccentricity wave-lengths. It is likely that observed lags in ice volume relative to orbital forcing, can be explained by variable response times to loading stress in the earth's upper mantle. Pisias and Moore (1981) suggest that the extent of marine-based ice sheets, as a function of glacial erosion, contributes to the effectiveness of orbital variations in regulating ice volume.

Several recent studies have documented the occurrence of cyclicity in climatic indicators at still shorter time-scales. Two cycles related to the precession factor (~2.3×10^4 and ~1.9×10^4 years) have been recognised by Hays et al. (1976) and Kominz et al. (1979). Hays and his colleagues assigned about 10 per cent of total variability in oxygen isotope records to these precession cycles. However, as pointed out by Broecker (1979), the precession effect is out-of-phase for the two hemispheres while oxygen isotope records for bipolar marine and ice cores (e.g. Johnsen et al. 1972) appear to vary in-phase.

Both Rooth et al. (1978) and Kominz et al. (1979) determine a dominance of peaks near 2×10^4 and 4×10^4 years in spectral analyses of marine sediments; they assign these to the precession and obliquity components respectively of the Milankovitch scheme. Obliquity would appear to be the more important, owing to simultaneous effects in both hemispheres and particularly in high latitude summers. However, both studies indicate that more than half of the climatic variance is either stochastic in nature or may be explainable by cycles of an unspecified but non-orbital nature operating over periods of 5000 years or less.

Conclusions

1. Timing of the long-term tectonic effect on climate evolution has been random over the last 10^9 years, and has operated by altering the latitudinal distribution of land and sea, by affecting the level of the sea and the importance of ocean currents, and by contributing to orographic and continentality effects.
2. Among the detected cycles in subantarctic climates, the longest appears to have a period of about 10^5 years. This has been a major cycle over the last 10^6 years but it is not recognised definitely in older rocks.
3. The prominent and important 10^5 year cycle is not correlated certainly with the Milankovitch parameters (particularly not with eccentricity of the orbit), but longer geologic records need to be investigated.
4. The 4×10^4 year obliquity cycle appears to be the most significant among recognised cycles, owing to its simultaneous effects in both hemispheres and to its known influence on ice growth through effects on high-latitude summer temperatures.
5. Precession cycles of 2×10^4 years are clearly recognised in the geologic record in subantarctic cores.
6. The cause of the 10^5 year cycle is presently unknown and causes are being sought in geophysical models of upper mantle stressing and relaxation in response to ice loading and melting.

References

Barron, E. J., Sloan II, J. L. and Harrison, C. G. A. 1980. Potential significance of land-sea distribution and surface albedo variations as a climatic forcing factor. *Palaeogeog., Palaeoclim., Palaeoecol., V. 30,* 17–40.

Broecker, W. S. 1979. The cause of glacial to interglacial climatic change. In *Proceedings, Evolution of Planetary Atmospheres and Climatology of the Earth, Nice.* 165–90.

Frakes, L. A. 1978. Cenozoic climates: Antarctica and the Southern Ocean. In Pittock, A. B. et al. eds, *Climatic Change and Variability: A Southern Perspective, 1978.* Cambridge University Press, 53–68.

Frakes, L. A. 1979. *Climates Throughout Geologic Time.* Amsterdam, Elsevier, 310 pp.

Frakes, L. A. and Kemp, E. M. 1973. Palaeogene continental positions and evolution of climate. In Tarling, D. H. and Runcorn, S. K. eds, *Implications of Continental Drift to Earth Sciences, 1, 1973.* London, Academic Press, 539–59.

Hays, J. D., Imbrie, J. and Shackleton, N. J. 1976. Variations in the Earth's orbit: pacemaker of the Ice Ages: *Science, 194,* 1121–32.

Johnsen, S. J., Dansgaard, W., Clausen, H. B. and Langway, C. C. 1972. Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature, 235,* 429–34.

Keany, J. and Kennett, J. P. 1972. Pliocene-early Pleistocene paleo-climatic history recorded in Antarctic-subantarctic deep-sea cores. *Deep Sea Res., 19,* 529–48.

Kominz, M. A., Heath, G. R., Ku, T. L. and Pisias, N. G. 1979. Brunhes time scales and the interpretation of climatic change. *Earth Plan. Sci. Letters, 45,* 394–410.

Manabe, S. and Hahn, D. G. 1977. Simulation of the tropical climate of an ice age. *J. geophys Res., 82,* 3889–911.

Pisias, N. G. and Moore, T. C., Jr. 1981. The evolution of Pleistocene climate: a time series approach. *Earth Plan. Sci. Letters, 52,* 450–8.

Rooth, C. G. H., Emiliani, C. and Poor, H. W. 1978. Climate response to astronomical forcing. *Earth Plan. Sci. Letters, 41,* 387–94.

Schnitker, D. 1980. Global paleoceanography and its deep water linkage to the Antarctic glaciation. *Earth-Sci. Reviews, 16,* 1–20.

Shackleton, N. J. and Kennett, J. P. 1975. Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analysis in DSDP sites 277, 279 and 281. In *Initial Reports Deep Sea Drilling Project, 29,* Washington, D. C., 743–55.

Shackleton, N. J. and Opdyke, N. D. 1977. Oxygen isotope and palaeomagnetic evidence for early Northern Hemisphere glaciation. *Nature, 270,* 216–19.

Steiner, J. and Grillmair, E. 1973. Possible galactic causes for periodic and episodic glaciations. *Geol. Soc. Amer. Bull., 84,* 1003–18.

Thompson, S. L. and Barron, E. J., in press. Comparison of Creteaceous and present earth albedos: Implications for the causes of paleoclimates. *Jour. Geol. (1981).*

Vail, P. R. and Hardenbol, J. 1979. Sea-level changes during the Tertiary. *Oceanus, 22,* 71–9.

Vail, P. R., Mitchum Jr, R. M. and Thompson III, S. 1977. Seismic stratigraphy and global changes of sea level, 4: Global cycles of relative changes of sea level. In Payton, C. E. ed., *Seismic Stratigraphy — Applications to Hydrocarbon Exploration.* Amer. Assoc. Petrol. Geol., Mem. 26, 83–97.

Van Donk, J. 1976. ^{18}O record of the Atlantic Ocean for the entire Pleistocene Epoch. In Cline, R. M. and Hays, J. D. eds, *Investigation of late Quaternary Palaeooceanography.* Geol. Soc. Amer., Mem. 145, 147–63.

Williams, G. E. 1972. Geological evidence relating to the origin and secular rotation of the solar system. *Mod. Geol. 3,* 165–81.

Williams, G. E. 1975. Possible relation between periodic glaciation and the flexure of the galaxy. *Earth Plan. Sci. Letters, 26,* 361–9.