PALAEOCEANOGRAPHY

Broken greenhouse windows

Large and rapid global sea-level changes indicate that polar ice sheets may have ephemerally existed during the Cretaceous greenhouse climate. Two oxygen isotopic studies provide evidence for and against this conclusion.

Kenneth G. Miller

Long-term intervals of global greenhouse warmth — 100 to 200 million years (Myr) or more — have been attributed to high levels of atmospheric carbon dioxide. One such greenhouse world has been identified between about 250 and 33 Myr ago, with peak warmth in the Late Cretaceous period (about 100 to 80 Myr ago). In contrast, the later Cenozoic icehouse world was characterized by continental-scale ice, first in Antarctica and later in the Northern Hemisphere, and it is generally thought that the global warmth precluded the existence of continental ice sheets. Yet emerging evidence for at least ephemeral ice sheets preceding the greenhouse to icehouse transition has led us to wonder if the greenhouse world was always ice free, or if there were short periods of glaciation punctuating the warmth. Two recent papers take opposing sides: Galeotti and coauthors[1] argue for the growth and decay of small Antarctic ice sheets during the Cretaceous period (144 to 65 Myr ago), whereas Ando and coauthors[2] provide evidence opposing ice-volume changes.

Reconstructions of global sea level have presented an interesting challenge[3]: even during the greenhouse interval from 250 to 33 Myr ago, sea-level fluctuations of tens of metres occurred over periods of less than 1 Myr, and thus can only be explained by changes in continental ice volume. Globally, and over these time frames, sea level is controlled primarily by the growth and decay of continental ice sheets, which store water on land and lower sea level as they grow. Thus, in a warm greenhouse world, sea-level changes of this magnitude would not be expected to occur. However, stratigraphic evidence and marine carbonates from the Cretaceous have begun to indicate the occurrence of just these sorts of sea-level swings, suggesting the presence of 'cool snaps', replete with continental ice, in the greenhouse world.

Stable oxygen isotopic ratios ($\delta^{18}O$) of sea water, which are preserved in marine carbonates such as chalks and fossil shells, are an indicator of the growth and decay of continental ice. A shift to heavier $\delta^{18}O$ values indicates that ice sheets are growing, entraining water on the continents and lowering sea level. However, such reconstructions are not perfect records of sea level, and are also affected by temperature and local variables.

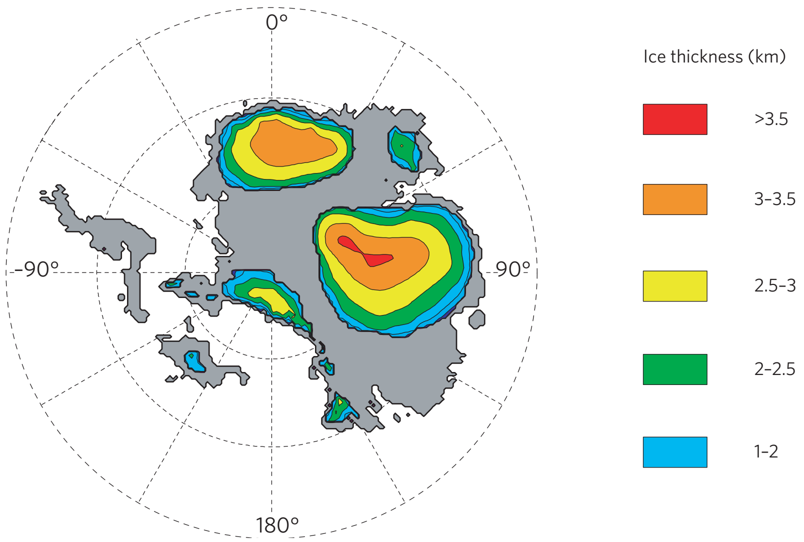

Figure 1 | A greenhouse ice sheet on Antarctica. Galeotti and coauthors[1] describe relatively small (~25 m) fluctuations in sea level, which they associate with the growth of an ice sheet on Antarctica. To cause such a sea level drop ~5–10 million km^3 of ice would need to build up on Antarctica. Ice would most likely build up in areas near a coastal moisture source and/or in areas of high topography[15].

Bulk carbonate $\delta^{18}O$ records[4] from the Contessa Quarry, Italy (from the Tethys Sea) provided the first hint of ice-volume changes during the Cretaceous period, though it was unclear whether these isotopic compositions reflected global or local processes. In another single-region study in New Jersey, records of sea-level fluctuations during the greenhouse interval were linked temporally with $\delta^{18}O$ increases, indicating a connection between ice sheets and sea level[5–7]. But the 'cool snaps'[8] remained speculative because of uncertainties in linking global sea level and $\delta^{18}O$ records.

In a recent paper, Galeotti and coauthors[1] provide new data from Italy in support of the existence of Cretaceous ice sheets. They temporally link a stratigraphic record of sea-level change from a shallow carbonate platform that formed in the Tethys Sea with a $\delta^{18}O$ record from bulk carbonates. In this setting, surfaces of erosion, which are readily apparent in the rocks, are created when sea level falls and the platform sediments are exposed to the air.

Galeotti and coauthors find that erosional events in the mid-Cenomanian (about 95 Myr ago), mid-Turonian (about 92 Myr ago) and Coniacian (about 88–89 Myr ago) ages — which represent three of the four largest Cretaceous sea-level falls — are temporally correlated to records of sea-level drops from other ocean basins[5–7,9,10]. Even more importantly, Galeotti and coauthors[1] firmly link the mid-Turonian event with an increase in carbonate $\delta^{18}O$, suggesting that an ice-volume increase caused this sea-level fall. Indeed, isotopic records from the tropical Atlantic Ocean, used in conjunction with an independent proxy of sea surface temperature[11], support their interpretation of a global sea-level fall during the mid-Turonian caused by the growth of continental ice.

Yet, although these inter-regional correlations seemingly support the growth of continental ice, the link between sea level and continental ice during the Cretaceous remains vigorously debated. A $\delta^{18}O$ reconstruction from the Cenomanian age failed to identify higher values associated with the sea-level fall[12], although the data were later reinterpreted as being consistent with a seawater $\delta^{18}O$ change on the order of ~0.2–0.3 ‰ (ref. 13), which could allow for Antarctic ice growth.

The most recent paper to enter the fray comes from Ando and coauthors[2], who analysed the $\delta^{18}O$ of carbonate shells from both surface- and bottom-dwelling foraminifera. They used closely spaced samples of a relatively well-preserved mid-Cenomanian section from Blake Nose, Florida. Their work showed an increase in $\delta^{18}O$ values in the bottom-dwelling foraminifera during the sea-level change, but no accompanying increase in the surface dwellers. As shifts in seawater $\delta^{18}O$ should be reflected throughout the water column, they question the interpretation of ice-sheet growth as a driver of this sea-level fall.

Part of the discrepancy between the studies may lie in the small magnitude of the global sea-level fall, estimated to be about 25 m. The seawater $\delta^{18}O$ change predicted for such a drop at this time is also small (<0.25‰) and near the detection limits. Yet, $\delta^{18}O$ shifts in the shells of surface dwellers have been detected at other low-latitude sites for other proposed periods of ice growth[11,14], and it is surprising that no change was observed during the Cenomanian at this site.

One of the primary challenges to any study of the links between sea level and ice volume during the Cretaceous is chronology. Both research groups were careful to bracket the events they described using biological and chemical stratigraphic constraints[1], and microfossil and carbon isotope analyses[2]. These excellent temporal correlations, together with those of Gale and coauthors[10], provide confidence that the sea-level changes were global, and that their $\delta^{18}O$ records can be tied to the sea-level events recorded in various locations.

So although the isotopic records remain to be reconciled, it does seem that our view of greenhouse intervals as long monotonic periods of warmth is incorrect. The 'cool snaps' indicated by Galeotti and coauthors' study (among others) were relatively short, lasting less than 200,000 years during a 1–2 Myr interval[11], and the associated $\delta^{18}O$ increase suggests they only require small ice sheets on Antarctica (for example, equivalent to one-third of the modern Antarctic ice sheet[5–7], Fig. 1).

Galeotti and coauthors[1] compare oxygen isotopes and stratigraphy to show that the mid-Turonian sea-level fall was driven by ice-sheet growth, and evidence from other sea-level falls[10] supports the global nature of this event[11]. It is, however, puzzling that the sea-level fall in the mid-Cenomanian described by Ando and coauthors[2] does not show a similar $\delta^{18}O$ shift to the other Cretaceous greenhouse events; a resolution of this question awaits further studies of this enigmatic interval. ❐

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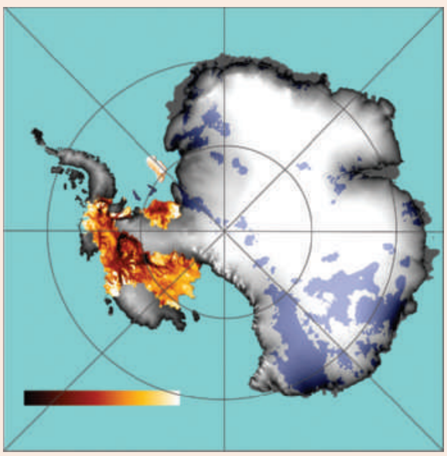
GLACIOLOGY

Melt revisions

Kilometres of ice have built up over Antarctica. From today's perspective, the vast sheet of ice and snow looks like an eternal feature. Yet the part of Antarctica that lies west of the Transantarctic Mountains is largely below sea level today, and its ice sheet has probably collapsed at least partly during past warm episodes. The West Antarctic ice sheet has therefore been flagged as a possible location of exceptional climatic sensitivity where a large mass of land-based ice may be lost to the ocean in response to relatively moderate changes in climate.

According to the fourth assessment report from the Intergovernmental Panel on Climate Change, global sea level would rise by about 5 m if the West Antarctic ice sheet were to collapse. However, Jonathan Bamber, of the University of Bristol, and colleagues have estimated the potential rise in global mean sea level from the disintegration of this ice sheet at only about 3.3 m (*Science* **324,** 901–903; 2009).



They base this value on a detailed reassessment of the volume of potentially vulnerable ice: ice resting on bedrock below sea level (the brown colours in the image) that slopes downwards inland. According to the so-called marine ice-sheet instability hypothesis, land ice under these conditions can be subject to rapid and irreversible removal if the buttressing ice shelves — such as those holding the West Antarctic ice sheet in place — disintegrate.

A sea-level rise from West Antarctic ice-sheet collapse would not be globally uniform. Mainly because of the ice mass's gravitational pull on the surrounding oceans, Bamber and colleagues project regional sea-level rise to be about 25% above the global mean (or about 4 m in absolute terms) along the US Pacific and Atlantic coasts. In contrast, coasts at the tip of South America would only be affected by about half the global mean rise.

But even with this lower estimate, a potential disintegration of the West Antarctic ice sheet would affect millions of people around the world who live in low-lying areas.

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