The Antarctic climate record

The Antarctic deuterium record for the past 800 ka is shown in Figure 1, along with an estimate of Antarctic temperature derived from it (Jouzel et al., 2007), and the classic benthic marine oxygen isotope stack (Lisiecki and Raymo, 2005). The latter record represents a combination of the oxygen isotope content of the ocean (which is controlled by global ice volume), and the fractionating effects of incorporation into shells (which is controlled by deepwater temperature).

The most obvious feature of the past 800 ka is that climate (as represented in both ice and ocean) has a variability dominated by the occurrence of relatively short warm interglacial periods approximately every 100 ka. The Holocene (which we are in now) is the latest of these interglacials. The similarity between the records shows that at these long climate periods we are seeing a global climate signal: when there is more ice in the world, predominantly over North America and Eurasia, there are also colder temperatures in Antarctica. The origin of the 100 ka cyclicity is widely believed to be related to astronomical cycles (Milankovich and related theories) (e.g., Imbrie et al., 1993). However, it remains a matter of debate why the relatively weak 100 ka period is seen more strongly than the 100 ka period (latter).
larger changes to insolation; and the mechanisms that amplify a small insolation change into a large climate change are also much debated.

Whatever the origin of the 100 ka cyclicity, it is not the case that every cycle is the same. The ice core record has particularly highlighted the differences between different interglacial periods. The 4 interglacials before 450 kyr appear weaker than those that follow, whereas the glacial maxima have less variability in the Antarctic record. The interval between warm periods is also not uniform. No clear explanation for the change in style of interglacials around 450 ka ago has yet emerged (Jouzel et al., 2007).

A final feature that is clear from the Antarctic record is the existence of millennial scale variability, particularly within the glacial periods. The signal has been shown (EPICA Community Members, 2006) to be closely associated with the larger millennial scale variability observed in Greenland (North Greenland Ice Core Project Members, 2004) and other northern hemisphere records, the so-called Dansgaard-Oeschger (D-O) events. These events of rapid warming (more than 10° within decades in Greenland) seem to occur at the apex of slower Antarctic warmings; once Greenland climate has jumped, Antarctic temperature slowly falls again. This pattern has been considered diagnostic of changes in ocean heat transport, with the Southern Ocean building up heat during periods when the heat is not transported northwards (Stocker and Johnsen, 2003). Whatever the cause, this pattern of millennial scale variability is the dominant feature seen in climate records at timescales below those of the orbital cycles.

**Trace gases and other signals**

As already stated, a unique feature of ice cores is that they contain a direct record of the trace gas content of the atmosphere. CO₂ is obviously a crucial gas for radiative forcing, but is also a diagnostic of whether we understand the carbon cycle and the oceans that host many aspects of it. CH₄ is another important greenhouse gas, and is also indicative of whether we have correctly assessed aspects of the terrestrial environment. Both gases have so far been reported for the past 650 ka (Figure 2). At the time of writing, the records to 800 ka are being prepared, and tied to the new EDC3 age scale. However, here I show the published data, which are on the old EDC2 age scale and can therefore not be compared directly to the climate record.

CO₂ particularly shows (Siegenthaler et al. 2005) a remarkable similarity to Antarctic temperature, with both the glacial-interglacial changes, and the same pattern of interglacials. The CO₂ concentration is typically 280–300 ppmv in warm interglacials, and only 240–250 ppmv in “weak” interglacials. CH₄ also shows (Spahni et al. 2005) a similar pattern, but with a much greater variability at millennial scale within glacial periods, because CH₄ shows up D-O events.

The similarity of CO₂ to Antarctic temperature (without the characteristics more reminiscent of the north) strongly suggests that the Southern Ocean exerts the main control on glacial-interglacial CO₂ changes, although a wide range of physical and biogeochemical processes are still mooted to explain the signal (Archer et al., 2000). Both gases, but particularly CO₂, probably played a significant role in amplifying the small externally-derived insolation changes into the large climate swings that are seen.

It is difficult to derive an exact phasing between changes in temperature and changes in CO₂ because the age of the trapped gas is different from that of the ice that surrounds it. However, for the warming transitions into interglacials, the best estimate (although currently under scrutiny) is that the start of the CO₂ increase lags temperature by around 800 ± 600 years (e.g., Monnin et al., 2001). Because the preceding statement is often misunderstood, it is important to emphasise that the increase in CO₂ and temperature at each termination lasts for around 5 ka. For most of this period, both are rising in parallel, consistent with the idea that, after a small increase in temperature caused by external factors, the two parameters formed an amplifier in positive feedback, with the temperature causing a lagged increase in CO₂, and the CO₂ acting to increase the temperature further.

Many other parameters can be measured on ice cores (as indeed on marine and terrestrial records covering the same period). These give information on aspects of the environment such as sea ice, ocean biogeochemistry and dust transport (Wolff et al., 2006). In
Figure 2, we have included as an example the non-sea-salt Ca flux, which is an indicator of the flux of dust deriving from South America: this record is an important input for studies of dust radiative forcing, and the effects of iron fertilisation of the ocean.

Conclusion

Ice cores are a key data source for the later parts of the Quaternary, providing an anchor of Antarctic temperature and some of the most important forcings. These data, when combined with data from other archives, make this time period highly amenable to modelling and hypothesis testing. The ice core community has formulated ambitious plans for future studies encompassing a range of timescales (Brook and Wolff, 2006). One part of this would aim to find a site where the ice core record could be extended to perhaps 1.5 Ma, and into the section (clearly seen in the marine record) where the 100 ka cycles give way to 40 ka periodicity. Understanding the reason for this change is a key issue in Quaternary science, and discovering how CO₂ and Antarctic climate changed during the transition is widely assumed to be a crucial part of the answer.

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