Palaeoclimate

Fresh evidence in glacial-cycle debate

Ancient air challenges prominent explanation for a shift in glacial cycles

An analysis of air up to two million years old, trapped in Antarctic ice, shows that a major shift in the periodicity of glacial cycles was probably not caused by a long-term decline in atmospheric levels of carbon dioxide. See Article p. XXX

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During the past 2.6 million years, Earth's climate has alternated between warm periods known as interglacials, when conditions were similar to today, and cold glacials, when ice sheets spread across North America and northern Europe. Before about a million years ago, the warm periods recurred every 40,000 years, but after that, the return period lengthened to an average of about 100,000 years. It has often been suggested that a decline in the atmospheric concentration of carbon dioxide was responsible for this fundamental change. On page XXX, Yan *et al.*[1] report the first direct measurements of atmospheric CO_2 concentrations from more than a million years ago**.** Their data show that the maximum CO_2 concentrations during interglacials did not decline, and that CO_2 levels during glacials stayed well above the lows that occurred during the deep glacials of the last 800,000 years. The explanation for the change must therefore lie elsewhere.

Understanding what caused the shift in periodicity, known as the mid-Pleistocene transition (MPT), is one of the great challenges of palaeoclimate science. The 40,000-year periodicity that dominated until about a million years ago is easily explained, because the tilt of Earth's spin axis relative to its orbit round the Sun varies between 22.1 and 24.5° with the same period. In other words, before the MPT, low tilts led to cooler summers that promoted the growth and preservation of ice sheets.

But after the MPT, glacial cycles lasted for 2–3 tilt cycles. Because the pattern of variation in Earth's orbit and tilt remained unchanged, this implies that the energy needed to lose ice sheets[2] had increased. One prominent explanation[3] is that atmospheric levels of CO_2 were declining, and eventually crossed a threshold value below which the net cooling effect of the decline allowed ice sheets to persist and grow larger.

Ancient air trapped in Antarctic ice can be extracted from cores drilled from the ice sheet, allowing the CO_2 concentration to be measured directly, but the ice-core record extends to only 800,000 years ago[4]. Estimates of CO_2 concentration from periods earlier than this have been made by measuring the ratio of boron isotopes in shells found in ancient marine sediments[5,6]. This indirect proxy measurement depends on a chemical equilibrium controlled by ocean acidity, which, in turn, is closely related to the atmospheric CO_2 concentration.

But the inferences of such measurements are necessarily imprecise and must be verified using more-precise, direct measurements. Scientists have therefore formulated plans[7] to find and retrieve deep ice cores that reach back to before the MPT. One project has recently been funded by the European Union, and hopes to retrieve million-year-old ice in 2024.

Yan *et al*. tried to bypass this effort by finding similarly old ice nearer the surface of Antarctica. In regions known as blue ice areas, the combination of ice flow against a mountain barrier, and surface ice loss by wind scouring and sublimation, leads to upwelling of old ice towards the surface. The authors therefore studied two cores, 147 and 191 metres deep, that were drilled to bedrock in the blue ice region near Allan Hills in Antarctica.

The researchers improved and applied a relatively new method[8] to date this old ice. The concentration of argon-40 in Earth's atmosphere is slowly increasing with time as it is produced from the radioactive decay of potassium-40. By measuring the ratios of argon isotopes in air extracted from cores, the age of ice can be determined. The authors also measured the ratios in the ice of deuterium to hydrogen, which can be used as a proxy of temperature at the time the ice was deposited.

Yan and colleagues thus concluded that ice in the lowest 30 m of each core is up to 2.7 million years old. However, the uncertainty of 100,000 years in this dating precludes their samples from being matched to particular parts of Earth's tilt cycle. Moreover, the authors found abrupt age discontinuities with depth in the cores, which suggests that the layers of ice within it have been disturbed. The authors therefore treated the measured concentrations of deuterium and CO_2 as snapshots of climate and atmospheric composition with an approximate age rather than as ordered time series. On the basis of the deuterium values, they make a plausible case that the observed range of measured CO_2 values represents most of the actual glacial–interglacial range.

Unfortunately, in the oldest ice samples, there was evidence that the CO_2 concentration had been artificially enhanced by gas produced from organic material at the base of the ice sheet. A few samples from about 2 million years ago were potentially not affected by this issue, but were insufficient in number to draw any conclusions. However, the authors obtained values for around 1 million and 1.5 million years ago that they consider to be undisturbed by added CO_2. In both periods, the maximum CO_2 concentrations are similar to those of interglacials from the last 500,000 years, peaking at 279 p.p.m. But the minimum value of 214 p.p.m. is much higher than the lows of around 180 p.p.m. that occurred in recent glacial maxima (the periods that corresponded to the maximum extent of ice). The authors conclude that the relationship between CO_2 levels and Antarctic temperature was very similar before and after the MPT.

The fact that the pre-MPT ice does not contain very low deuterium/hydrogen ratios characterising very cold Antarctic temperatures, or low CO_2 levels characteristic of recent glacial maxima is probably just a consequence of the shorter period of the glacial cycles. Such low values are not generally found in the first 40,000 years of post-MPT glacial cycles either. Although Yan and colleagues' data points cannot be placed within a tilt cycle, it seems likely that the CO_2 concentrations are not very different at the crucial points in cycles when the ice sheet is either lost (before the MPT) or continues growing (after the MPT). This forces us to look elsewhere for the cause of the longer cycles, perhaps refocusing efforts on understanding whether changes to the nature of the ice-sheet bed caused by glacial erosion[8] altered the characteristics of the ice sheets and their vulnerability to melting.

Yan and colleagues' data add much-needed precision to the previously reported estimates of CO_2 levels made using data from marine sediments[5,6]. However, the authors' tantalizing snapshots of the pre-MPT world emphasize the need for a complete, undisturbed time series of greenhouse-gas concentrations that can be put into context with the climate cycles at that time. Hopefully the planned new ice cores will provide that.

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