What drives climate?

Lee R. Kump

Variation in the amount of CO_2 in the atmosphere is usually taken to be the main cause of climate change on geological timescales. The apparent exceptions to the link threaten to undermine that view.

In a worst-case scenario, fossil-fuel burning will pump up concentrations of CO_2 in the atmosphere to levels higher than those of the past several tens of millions of years[1,2]. Hence the intense research on the long-term behaviour of the carbon cycle. The aim is to understand the relationship between changes in atmospheric concentrations of CO_2 and climate swings from 'icehouse' (presence of large continental ice sheets) to 'greenhouse' (ice-free) conditions over the Phanerozoic eon — the past 544 million years of Earth's history. Various geochemical measurements and numerical models of the carbon cycle have been used to reconstruct ancient CO_2 levels[2]; such measurements are known as proxies because they are indirect, in this case being based on the carbon isotopic composition of soil minerals or organic matter in marine sediments. Climate reconstructions, of temperature in particular, have largely been derived from a rather incomplete record from fossil and geological indicators[3].

On page 698 of this issue, Veizer *et al.*[4] present an exquisite temperature record that is based on the oxygen isotopic composition of tropical marine fossils and that broadly mimics the inferred oscillations of global climate on 100-million-year timescales. However, calculations using proxy data for atmospheric CO_2 reveal mismatches with both the climate and the oxygen isotope records. Veizer *et al.* thus cast doubt on the prevailing view that most, if not all, of the climate swings in the Phanerozoic have been linked to variations in atmospheric CO_2.

There are two primary stable isotopes of oxygen, the more abundant ^{16}O and the less abundant ^{18}O. Isotopic compositions of various materials are reported as $\delta^{18}O$, a standardized ratio of $^{18}O/^{16}O$. Marine fossils acquired their oxygen isotopic composition when the organism was alive and accumulating calcium carbonate or silica from sea water to make its shell or skeleton. The $\delta^{18}O$ of this material reflects both the isotopic composition of the sea water in which the organisms lived, and the extent of preferential uptake of the isotopes during calcification or silicification; that uptake depended on the water temperature and other physiological factors that can be species-specific. During and after fossilization, however, fluids in sediment pores can shift oxygen isotopic compositions away from the original value, potentially compromising the fossil's value as an indicator of temperature.

Veizer *et al.*[4] have been very selective in their sample selection and analysis, using only those fossils that pass several criteria of preservation[5]. Nevertheless, they observe a long-term (100-million-year or more) trend of decreasing $\delta^{18}O$ with sample age that many would argue reflects the greater likelihood that the older samples have undergone post-depositional alteration. Veizer *et al.* discount that conclusion. They 'de-trend' the data, though, because they feel that the long-term trend is caused by tectonic processes, not climate. This then allows them to concentrate on the oscillations of $\delta^{18}O$ that coincide quite nicely with climate swings during the Phanerozoic, as inferred from indicators such as the occurrence and distribution of glacial deposits and climate-diagnostic fossil assemblages. This correspondence is encouraging, because it justifies the use of the isotope record to fill in the gaps in the other, relatively discontinuous climate records. Taken at face value, the isotopic swings imply that the temperature of the sea surface in the tropics (the habitat of most of the fossilized organisms studied) has varied by as much as 13 °C over the Phanerozoic.

Veizer *et al.* acknowledge that part of the record must reflect changes in ice-sheet size. That is, the $\delta^{18}O$ of the ocean increases as ice sheets preferentially extract H_2O with ^{16}O from the oceans as they grow, which increases the $\delta^{18}O$ of the shell of the organism independently of any temperature effects on $\delta^{18}O$. Taking the ice-volume effects into consideration, they conclude that sea surface temperatures in the tropics varied by about 9 °C in the Phanerozoic. The inference here is that climate change has been global, rather than being restricted to high latitudes where the direct effects of ice-sheet expansion and retraction are greatest.

Not content with this result, important though it is, the authors went further. They proceeded to address the question of whether the variations in atmospheric CO_2 inferred from carbon isotopic proxies are

Earth science

Not making waves

When Bill Gates got married on the Hawaiian island of Lana'i, he might have wondered how the coral-rich gravel outcrops shown here came to be 30 metres above sea level. If so, he would have been told that these gravels, and others even higher up, were deposited by a giant tsunami 105,000 years ago.

The tsunami hypothesis came from the chaotic nature of the gravels, and the fact that other nearby Hawaiian islands are subsiding — so that deposits formed at sea level 100,000 years ago would not be expected to be at high elevations today. But the tsunami would have had to be truly 'giant', with a run-up of hundreds of metres, compared with a modern-day Hawaiian record of only 17 metres.

Elsewhere in this issue (*Nature* **408,** 675–681; 2000), Ken Rubin and colleagues describe a test of the tsunami hypothesis. They find that the gravels contain corals of two distinct ages (135,000 and 240,000 years old), both from times when sea level was high. From this and detailed mapping studies, they conclude that the gravels were in fact deposited not in a single catastrophic event, but by typical Hawaiian coastal processes such as those forming the cobble beach towards the left of the photo.

And what of the subsidence problem? It turns out that recent flexure models of the Pacific plate can explain concurrent subsidence of some islands and uplift on others, including Lana'i. Uplifting experiences for both the island and the computer magnate, then. **Laura Garwin** consistent with the climate history from oxygen isotopes and the general notion that CO_2 is a fundamental driver of climate. They use an energy-balance climate model incorporating the proxy record of atmospheric CO_2 to determine tropical sea surface temperatures during the Phanerozoic. The temperatures predicted with this model bear little resemblance to the climate record. Either the CO_2 proxies are flawed, or our understanding of the relationship between CO_2 and climate (as expressed in the climate model) needs rethinking. From the title of their article, "Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoic eon", the authors evidently feel that CO_2 may not be the climate driver it has been made out to be.

Such a conclusion deserves close scrutiny, because the policy implications are huge. The geological record is our best hope of establishing a correspondence between atmospheric levels of CO_2 and climate, and understanding the likely consequences of fossil-fuel burning. If large changes in atmospheric CO_2 in the past have not produced the climate response we thought they had, that undermines the case for reducing fossil-fuel emissions.

The authors concentrate on two mismatches: the glaciation of the Late Ordovician period (440 million years ago) and the cool climate of the Jurassic and early Cretaceous (approximately 220–120 million years ago), both of which coincided with proxy indications of high levels of atmospheric CO_2. These seeming paradoxes are not new, however, and the Late Ordovician mismatch has been particularly well studied[6,7]. Solar physicists argue that the Sun was then some 5% less luminous than it is today, so higher atmospheric CO_2 would have been necessary simply to prevent runaway 'icehouse' conditions. Moreover, the glaciation was extremely short-lived[8], so the available proxies may not pick up a possible reduction in levels of CO_2 during that brief period. CO_2 has a short residence time in the atmosphere, and a transient reduction in atmospheric CO_2 is a viable explanation for the glaciation[9].

The Jurassic mismatch is a more persistent and problematic feature. There is also a notable mismatch during this time interval between the proxy data, which indicate greatly increased concentrations of CO_2, and more moderate estimates that come from models of the carbon cycle[10]. So levels of atmospheric CO_2 may not have been as high as the proxies indicate. Nevertheless, the cool climate of the Jurassic remains something of a mystery.

Clearly, factors other than atmospheric CO_2 can influence climate on geological timescales. Continental drift creates supercontinents and breaks them into smaller fragments, gives birth to mountain belts and high plateaux, and shifts the distribution of continents among latitudinal belts and hemispheres. All of these factors affect the atmosphere and the ocean circulation, as well as the intensity of the hydrological cycle, which ultimately dictates the cloudiness of the planet and its ice-cap coverage. These changes in the water cycle also alter the reflectivity of Earth as a whole, and can therefore affect global climate.

When we put everything we know into models of the carbon cycle, though, we predict changes in atmospheric CO_2 that largely parallel inferred climate shifts. So the lack of close correspondence between climate change and proxy indicators of atmospheric CO_2 may force us to re-evaluate the proxies, rather than disavow the notion that substantially increased atmospheric CO_2 will indeed lead to marked warming in the future. ■

Lee R. Kump is in the Department of Geosciences and the Astrobiology Research Center, 503 Deike Building, Pennsylvania State University, University Park, Pennsylvania 16802, USA.
e-mail: lkump@psu.edu

1. Walker, J. C. G. & Kasting, J. F. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **97,** 151–189 (1992).
2. Berner, R. A. *Am. J. Sci.* **294,** 56–91 (1994).
3. Frakes, L. A., Francis, J. E. & Syktus, J. I. *Climate Modes of the Phanerozoic* (Cambridge Univ. Press, 1992).
4. Veizer, J., Godderis, Y. & François, L. M. *Nature* **408,** 698–701 (2000).
5. Veizer, J. *et al. Chem. Geol.* **161,** 59–88 (1999).
6. Crowley, T. J. & Baum, S. K. *J. Geophys. Res.* **100,** 1093–1101 (1995).
7. Gibbs, M. T., Barron, E. J. & Kump, L. R. *Geology* **25,** 447–450 (1997).
8. Brenchley, P. J. *et al. Geology* **22,** 295–298 (1994).
9. Kump, L. R. *et al. Paleogeogr. Palaeoclimatol. Palaeoecol.* **152,** 173–187 (1999).
10. Berner, R. A. *Science* **276,** 544–547 (1997).

Human evolution

A start for population genomics

S. Blair Hedges

The most thorough analysis yet of the divergence of sequences in human mitochondrial DNA has been carried out. The results support the view that modern humans originated in Africa.

When and where did our species arise? Over the past two decades molecular evolutionists have vigorously pursued this question. DNA evidence from the cell powerhouse known as the mitochondrion has figured prominently in these studies, with mutations providing the raw data for producing evolutionary trees and molecular clocks to time sequence divergence. The mitochondrial family tree of humans has suggested that our roots lie in Africa[1–3], but this tree has had only weak statistical support. Conversely, other researchers have proposed that modern humans arose simultaneously in different regions of the world[4].

Now, on page 708 of this issue, Gyllensten and colleagues[5] describe an analysis of the complete mitochondrial genomes of 53 people of diverse geographical, racial and linguistic backgrounds. At 16,500 base pairs, each sequence is much longer than those previously studied. The upshot is a robust tree rooted in Africa, which times the exodus from Africa to within the past 100,000 years (recent in evolutionary terms). With this result, the pendulum swings further towards the claim that modern humans, *Homo sapiens*, originated in Africa.

Our closest living relatives are African apes, so why is an African origin for modern humans controversial? The reason is that our immediate predecessors in the genus *Homo*, now extinct, are known to have wandered out of Africa as early as two million years ago. The main alternative to an African origin, the multiregional model, holds that modern humans arose simultaneously in Africa, Europe and Asia from these predecessors[4]. Proponents of this view argue that the fossil record indicates transitions between, for example, Neanderthals (*H. neanderthalensis*) and modern humans in Europe, and between *H. erectus* and modern humans in Asia. However, the existence of non-African transitional fossils is debatable[6,7], and there is genetic evidence[8] that Neanderthals did not widely interbreed with modern humans even though the two coexisted for at least 10,000 years. Such coexistence is the strongest evidence for recognizing the two as separate species.

The crux of the mitochondrial evidence for an African origin has been the presence of several African lineages deep in the evolutionary trees, even though they have only had weak statistical support. Gyllensten's team[5] also found this pattern, but obtained a robust tree by collecting a larger data set than in previous studies. The three earliest branches in their tree lead exclusively to Africans, and two of the splits are statistically significant. Interpreted literally, the tree indicates that some Africans are closer to Europeans and Asians than to other Africans. However, the history of a single gene or molecule may not always mirror that of the population, and other molecular studies place Africans in a single group[9]. Together, these studies suggest that the founding population leaving Africa carried with it a subset of mitochondrial alleles — alternative forms of the same gene — and that African populations continued to interbreed after the exodus.