Climate change and palaeoclimatology

And was there a mighty wind? (*January 2005*)

Readers will be familiar with the to-ing and fro-ing that surrounds the idea of Neoproterozoic Snowball Earth episodes from earlier diaries. The leading proponent and sturdy defender of the hypothesis, Paul Hoffman of Harvard University, re-enters the fray as co-author of a paper that builds on the idea that following global glaciation the climate became not only very warm but also violent (Allen, P.A. & Hoffman, P.F. 2005. Extreme winds and waves in the aftermath of a Neoproterozoic glaciation. *Nature*, v. **433**, p. 123-127; DOI: 10.1038/nature03176). They document evidence from "cap carbonates" in northern Canada and Spitzbergen that succeed diamictites of "Marinoan" (~635 Ma) age, in the form of large-scale sedimentary structures. Many of these are submarine ripples with amplitudes up to 40 cm, and forms that suggest they were produced by sea-bed motion due to surface waves, down to 200-400 m, far deeper than the modern, average storm-wave base. Central to their argument is hydrodynamic modelling of wind speeds that might have produced such large ripples, and their specific shapes – steep sided. Being based on experiment and observation of modern sea-bed processes, the theory seems quite rigorous. It retrodicts wave periods that are somewhat longer than those commonly seen in modern ocean storms. From that they derive sustained wind speeds that exceed 70 km per hour across open oceans, extraordinary by modern ocean wind standards.

Warming may have triggered Northern Hemisphere glaciation (*February 2004*)

While I write this entry it is supposed to be early spring outside, and that is clearly what the ducks reckon as well – they are beginning to, er um, frolic. But there has been two weeks of snow and frost. Britain and the rest of Europe owe the frigid snap to cold air spilling westwards from northern Asia; the influence of the Siberian winter high-pressure area. Although somewhat lost in the recent kerfuffles about whether or not global warming is a fact or a misreading of data, the inevitable build up of mid-continental cold dense air in winter might have interesting consequences, should climate warm. Normally, areas far from the oceans remain dry and cloudless bcome very cold through radiative heat loss in winter. When spring comes, such snow as there is soon disappears and the extremes of cold are replaced by surprisingly high summer temperatures. Should moist air find its way into such areas during winter, vastly more snow would fall. Its melting would take longer, and more solar radiation would be reflected back to space in spring. Such an albedo feedback could induce generalised cooling. Now evidence has emerged that the earliest known growth of land ice in North America was linked to warming of the ocean from which winds blew over it (Haug G.H. *et al*. 2005. North Pacific seasonality and the glaciation of North America 2.7 million years ago. *Nature*, v. **433**, p. 821-825; DOI: 10.1038/nature03332). In fact it is axiomatic that growth of continental ice sheets requires a supply of moisture and snow that exceeds the rate of summer melting and ablation, as well as cold winters.

Most theorising about the onset of Northern Hemisphere glaciation has centred on changes in North Atlantic circulation due to closures of the straits where the Isthmus of Panama now links North and South America, and the start of southward deep-water circulation from the latitude of Iceland. In fact both are known to have preceded the last Ice Age by a good 2 Ma. The actual start around 2.7 Ma coincided with an increase in obliquity of the Earth's orbit that would have led to periods with cold northern summers. Without abundant mid-continent snowfall, that in itself would not have set ice sheets forming in earnest. The multinational team of oceanographers studied sea-floor sediment cores from the sub-Arctic Pacific. To their surprise, sea-surface temperatures provided by evidence from planktonic organisms show evidence at 2.7 Ma for on the one hand cooling of the sea surface (from foraminifer oxygen isotopes) yet considerable warming on the other (from organic chemicals secreted by coccolithophores). Resolving this paradox requires a careful assessment of the ecological behaviour of the two groups of organisms.

The authors' explanation involves the onset of density stratification in the North Pacific, so that the surface warmed quickly in summer, retaining warmth during autumn, and warmed slowly in spring from its minimum temperature. Both result from the high thermal inertia of water. The productivity of silica-secreting diatoms plummeted to a fifth of its earlier levels at 2.7 Ma as well, explained by ocean stratification reducing the supply of nutrients from deep water upwellings. Intuitively, a warm sea upwind of the North American continental interior should have generated high snowfall in late autumn and winter. Haug and colleagues modelled the contrasting effects of an ocean with water overturn and mixing with one that tends to become stratified, to simulate snowfall over the North American Arctic. From a situation in the Pliocene with snowfall over Greenland and the Arctic islands, the scenario shifts to heavy snow over the whole Arctic in the earliest Pleistocene. It seems that the trigger for the Great Ice Age was a hemisphere away from the "usual culprit", the North Atlantic, although its vagaries, once glacial cycles were underway, probably controlled the details thereafter.

Did the earliest agriculture kick-start global warming (*March 2005*)

Most climate scientists encourage us to believe that planetary warming caused by gas emission from our energy intensive life style is both new and an inevitable context for our future. Yet, one leading authority on past climates, William Ruddiman of the University of Virginia, reminds us that it isn't only cars and power stations that release warming gases (Ruddiman, W.F. 2005. How did humans first alter global climate? *Scientific American*, v. **292** April 2005, p. 34-41). New evidence from air bubbles in the Vostok core through Antarctic ice shows a strange deviation of atmospheric CO_2 around 8000 years ago, from a downward trend in the early Holocene to one that relentlessly rises to the levels that characterised the recent pre-industrial world. At around that time early agriculturalists in Europe and China began to chop down forest to make fields, thereby releasing the carbon content of felled trees to the atmosphere as CO_2. By 5000 years before present, rice cultivation in East Asia had begun the release of methane from waterlogged paddy fields, and the methane content of ice bubbles reveals a reversal of methane decline at that time exactly.. Ruddiman's view is that the release of both "greenhouse" gases reversed a natural cooling trend, and that growing populations sustained growth in atmospheric CO_2 (methane is quickly oxidised in the atmosphere). Comparing the rising CO_2 of the Holocene with its records in ice-bubble for the previous three interglacials, shows that in each previous case the gas rose to a maximum early in the interglacials and then declined steadily.

The invention of agriculture and its spread from around 10000 years ago in the Near East, he claims, could have staved off the onset of global cooling and the climatic descent into another glacial epoch, by eventually adding 40 parts per million of CO_2 to the air. To support his hypothesis Ruiddiman compares the more recent ice-core records with historic catastrophes, mainly plagues that wiped out substantial proportions of the word population. Sure enough, there are falls in CO_2 at the time of each major plague; the Justinian Plague between 540 to 542 AD in Europe, the Black Death of the Middle Ages, and the reduction of the population of the Americas after 1493 by maybe 90% when "Old World" diseases such as smallpox and measles met no resistance among native peoples. In many respects Ruddiman's ideas seem plausible, until we see the data. The problem with ice core data is that its resolution degrades through time, and before 70000 years ago, no annual layers are preserved in glacial ice. Moreover, records from different Antarctic cores differ wildly for the historic period and Ruddiman does not show the record from Greenland ice. Finally, records of ice volume and ice-cap temperatures, derived from marine and glacial oxygen isotope records, show that each previous interglacial involved very different fluctuations in many other climate-related parameters. If nothing else, Ruddiman's ideas will be challenged although the issue will "run and run" until the next "big thing".

Making sense of glacial-interglacial cycles? (*March 2005*)

The competing periodicities of the three astronomical "drivers" of climate - orbital eccentricity (~100 ka), axial obliquity (~40 ka) and axial precession (~20 ka) – lie behind several models for the climate changes of the last 0.7 Ma. Taking in the theories that sway towards the influence of variables in the Earth system itself, around 30 models have some currency at present. Since climate forecasters have to take account of which factors drive climate in the absence of human emissions, as well as piece together their own particular models, it is easy to see how critics of global warming get a wide hearing: compared with creationists, they have it easy! Is there any way of resolving what is quite bluntly a theoretical mess? It is a mess simply because the available data are so complex, and in the case of both main sources, ocean-floor sediments and ice cores, not only are their devils in the detail, but there are whopping contradictions, such as the mismatches in timing between the Greenland and Antarctic ice cores. Add all the other sources, such as stalactites, tree rings etcetera, together with caveats like the difficulty in time calibration using ^{14}C dating, and the volume of diverse records become bewildering. It is tempting that a reversion to a statistical approach, that includes more bells and whistles than hitherto (see *Evolutionary rhythms* Palaeobiology March 2005), can resolve matters. Peter Huybers and Carl Wunch, of Woods Hole Oceanographic Institution and MIT, have tried that for pacing of the last 0.7 Ma of climate cycles (Huybers, P. & Wunsche, C. 2005. Obliquity pacing of the late Pleistocene glacial terminations. *Nature*, v. **434**, p. 491-494).

Generally accepted "wisdom" holds that the last 7 glacial-interglacial cycles were paced by ~100 ka eccentricity forcing, even though it has the weakest effect on solar heating, by a very long way. But there are smidgens of evidence for some interaction between that and the much stronger influence of changes in the Earth's axial tilt or obliquity. Huybers and Wunsch go for the Popperian rigor of first defining a null hypothesis, that obliquity has no effect, and then designing a test. It isn't easy to decide how the contrary hypothesis that it does can be evaluated though. The clearest features in all climate records are the ends of glacial epochs or termination: they are sudden, sharp and generally look the same. Most other features have some kind of pattern, but little consistent comparability. Using the most advanced statistical techniques, which employ many iterations to test for stability in statistical models, they can show that the null hypothesis fails. The positive result is that the time between terminations that are repeatedly modelled falls into two envelopes, around 120 and 80 ka, which simple arithmetic shows are divisible by 40 ka. But how can axial obliquity only have an effect every two of three of its cycles, while a single cycle does not appear in the time-series: Is it nature skipping beats somehow? One means that the authors suggest is that the underlying pace of eccentricity can effect the temperature at the base of ice sheets, depending on their thickness. If they are thin, then the heating is insufficient to trigger ice-sheet collapse because the base is very cold, whereas if ice is thick the effects of thermal conductivity and heat flow makes the ice base warmer and more subject to perturbation beyond its failure limit. It was at this point that I gave up, but wish the authors good luck in promoting their possibly unifying hypothesis for what finishes off glacial epochs…

Snowball Earth gets a boost (*April 2005*)

Since Paul Hoffman and others launched their hypothesis of successive Earth-enveloping glaciations during the Neoproterozoic Eon, that notion of "Snowball" conditions has received many severe knocks, charted by numerous items in earlier diaries. Geochemists and geologists from the Universities of Vienna and Witwatersrand realised that a good test of the hypothesis would be to concentrate on a rather obvious property of an ice-bound planet (Bodiselitsch, B. *et al*. 2005. Estimating duration and intensity of Neoproterozoic Snowball glaciations from Ir anomalies. *Science*, v. **308**. P. 239-242; DOI: 10.1126/science.1104657). Whatever falls on an ice sheet, whether it is cosmic dust from outside the Earth or ash from volcanoes, becomes trapped in the annual layers of ice. When the ice melts, that accumulated content is transferred to the oceans very quickly. With weathering in suspended animation during the glacial epoch, transport of many elements would have slowed to very low levels. So, marine sediments deposited immediately after the diamictites that are allegedly glaciogenic ought to contain anomalously high levels of several elements. The most important of these would be those which show very different abundance patterns in meteorites from those in terrestrial rocks such as iridium. Interestingly, it was Alvarez father and son who first tested the idea of investigating duration of sedimentation using iridium concentration, which led to their discovery of the K-Pg impact event.

Bodiselitsch *et al*. hit what seems to be "paydirt" in carbonates above a prominent diamictite in central Africa. Their samples are impeccable, being from diamond-drill cores produced during evaluation of sediment-hosted mineralization in the famous Neoproterozoic Copper Belt of Zambia and Congo. The core contains a prominent iridium anomaly at the very base of the carbonates, with a "signature" relative to other anomalous elements that points to a cosmic origin. Normally such an anomaly would be ascribed to a meteorite impact, but in this case the coincidence would be too good to be true. Instead, the authors use the magnitude of the anomaly to estimate how long cosmic dust had to accumulate to build up such a high level if it was released by rapid deglaciation. Deep-ocean sediments from the last 80 Ma are a guide to the long-term accumulation rate of cosmic material. If that rate is applied to the cap-carbonate anomaly, it gives a total time for accumulation in the hypothesised global ice cover of around 12 Ma; five times longer than the entire Pleistocene. Presumably this would have been from ice immediately overlying the area being studied. An ice age that long defies any idea of more "normal", astronomically forced glaciation. Such a connection would be expected to have cyclically formed and receded many times, thereby releasing the dust particles much more gradually. Any anomalies would be expected in the diamictites themselves, yet there are none. Although sample spacing is rather patchy through the entire succession, they are most dense around the anomaly itself. Moreover, another suspected glaciogenic "package" higher in the sequence shows exactly the same iridium "spike".

Arguing against such support for the "Snowball Earth" hypothesis will be difficult, but other sequences require similar tests, most importantly those of Namibia, where Hoffman and colleagues developed their ideas, and the much more extensive deposits of Australia. The Zambian diamictite sequence is reckoned to represent both postulated deep-freeze events of the Neoproterozoic, around 710 Ma (Sturtian) and 635 Ma (Marinoan). There is one nagging problem. Data from one area are likely to record ice-retained cosmic dust only from ice in its immediate vicinity, and therefore do not represent the entire planet. Much of the controversy is between supporters of a whole-Earth ice cover, and those who favour patchy glaciation (the "Slushball" model). Unfortunately, Neoproterozoic stratigraphic correlation and radiometric age calibration is not yet sufficiently good to detect the same intervals elsewhere and look for anomalies there. In fact, the stratigraphy is generally correlated from place to place by matching the diamictites themselves. But there is growing evidence that they may all coincide in time.

Tracking ocean circulation during the last glacial period (*April 2005*)

The use of various ocean-floor sediment proxies for climate change, such as the ups and downs of heavy ^{18}O that chart waxing and waning continental ice cover, has progressively revealed the complexity of shifts during glacial and interglacial periods. Yet more emerged from finer-resolution time-series contained with Greenland and Antarctic ice cores. The diversity of information that proxy for many different, climate-related processes has, in the last decade, enabled palaeoclimatologists to begin piecing together possible causative mechanisms, beyond the initial discovery of an astronomical signal in early oxygen-isotope records. One of enormous significance is the possibility that sudden millennial-scale cooling and warming link to changes in ocean circulation, especially that performed by the Gulf Stream driven by thermohaline processes at high northern latitudes. Shutting down that poleward transfer of heat, probably because fresh meltwater made high-latitude surface ocean water less dense, has been implicated in sudden cooling or "stadials", and its restart linked to warming or "or interstadials". The last such sudden climate event, the Younger Dryas between about 12 and 11 thousand years ago, is widely believed to have resulted from a collapse of the Gulf Stream. That has raised fears that current anthropogenic warming might achieve the same thing, thereby plunging Western Europe into a counterintuitive frigid period through loss of its maritime warming.

Ocean circulation has lacked a proxy that might help resolve such worrying scenarios, but it seems that one has arrived, because of improvements in mass spectrometry (Piotrowski, A.M. *et al*. 2005. Temporal relationships of carbon cycling and ocean circulation at glacial boundaries. *Science*, v. **307**, p. 1933-1938; DOI: 10.1126/science.1104883). Different bodies of ocean-surface water have subtly different chemical compositions, due to the varied geochemistry of surrounding landmasses. Weathering of exposed rocks results in some elements entering solution in river water, and that mixes with surface water in the nearby ocean. Among the most useful elements are those with an isotope to which radioactive decay of unstable isotopes of another element contributes. A good example is ^{87}Sr that is formed when ^{87}Rb decays. Where continents expose large expanses of very ancient rocks they contribute more ^{87}Sr to seawater than do continents veneered with younger rocks. Strontium isotopes have been used successfully for charting very-long term changes in the overall erosion of continental crust, in relation to climate shifts, but being related to calcium are taken up quickly by carbonate secreting organisms, such as foraminifera, at many different levels in the ocean as it circulates. So they are not very useful for short-term studies. A more useful isotopic system involving a daughter of slow radioactive decay is that of neodymium, because it does not get taken up in this way. It does however enter the manganese minerals that slowly precipitate on the deep ocean floor. Moreover, its isotopic composition varies greatly in different ocean-water masses. Piotrowski *et al*. used neodymium isotopes from deep ocean cores to see if changes in this circulation proxy coincided with known climate proxies. For interstadial, warming events there is a match, so a Gulf-stream control over millennial-scale climate shifts is indeed supported. But for the start and end of the full glacial period control by ocean circulation did not happen. Instead, changes in the neodymium record lag behind the climate proxies, suggesting climatic control of circulation, which then "kicked in" to boost changes that were well underway.

See also: Kerr, R.A. 2005. Ocean flow amplified, not triggered, climate change. *Science*, v. **307**, p. 1854; DOI: 10.1126/science.307.5717.1854a.

Thermal metamorphism and ocean anoxia (*May 2005*)

Now and again in the geological record, evidence turns up that suggests that the deep oceans were devoid of oxygen. Ocean anoxia encourages burial of dead organic remains that gives rise to carbon-isotope "excursions": signals of the anoxia itself. A likely mechanism that starves the deep oceans of oxygen is the shutdown of that part of the ocean "conveyor" driven by sinking of cold, dense brines that occurs today in the North Atlantic and around Antarctica. Gases dissolve more efficiently in cold water than in warm. Quite probably most oceanic anoxia events are related to global warming and increases in the "greenhouse" effect due to CO_2 rises in the atmosphere. A group of US and British geoscientists have examined one such anoxia event in the Lower Jurassic (~183 Ma) of Denmark using both carbon isotopes and the density of pores (stomata) on fossil leaves (McElwain, J.C. *et al*. 2005. Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals. *Nature*, v. **435**, p. 479-482; DOI:10.1038/nature03618). Stomatal density is inversely related to the amount of CO_2 in the atmosphere, so is very useful in seeking evidence for an anoxia-climate link.

This particular anoxia event has been linked either to release of methane, which quickly causes warming and then oxidises to CO_2, from gas hydrate or to massive release of carbon dioxide itself. McElwain *et al*. neatly show that the event first experienced drawdown of "greenhouse" gas and cooling of around 2.5 °C, then sudden quadrupling of CO_2 and warming of around 6.5°C. Such an odd pattern cannot eaily be ascribed to methane release, but coincides with the formation of the Karroo-Ferrar continental flood-basalt igneous activity in southern Africa and Antarctica. That involved massive intrusion into coal-bearing strata, whose thermal metamorphism would have released huge amounts of "greenhouse" gases. Calculations of the amount of carbon mobilised to cause the shifts in CO_2 suggest between 2.5 and 4.4 trillion metric tons, vastly more than the probable amount of methane hydrate beneath the Jurassic sea floor.

Another view of the Younger Dryas cooling event (*June 2005*)

High latitudes in the North Atlantic, especially on its eastern side, are warmed today by the Gulf Stream. That current, which defies the Coriolis effect, is pulled northwards by the sinking of cold dense sea water between Greenland, Iceland and Scandinavia to form North Atlantic Deep Water (NADW). The thermohaline circulation here is driven by both cooling of salty surface water in the Gulf Stream and further salinisation as sea ice forms in this area each winter. The Younger Dryas cold period between 13 and 11.5 ka is regarded by most oceanographers and climatologists to have resulted from sudden freshening of surface waters in the high-latitude North Atlantic, so that water density became too low to sink. Such a process had occurred several times during the last glacial period, each of which has been correlated with release of massive amounts of glacial ice as icebergs. Their melting fueled the freshening. The Younger Dryas is a different kind of event, because it occurred well into the period of global warming that brought the Ice Age to an end. A seemingly plausible explanation was suggested in 1989 by Wallace Broecker, involving an explosive release of meltwater trapped in glacial lakes roughly along the Canadian-US border that flowed down the present St Lawrence River Valley.

A problem with Broecker's mechanism is that sea-level records through the Younger Dryas show no sudden rise, whereas at about 14 ka a meltwater pulse had resulted in a 20 m rise over about 500 years, with no sign of a climatic response to a shutdown of the Gulf Stream by the freshening that it caused. A similar event occurred shortly after the waning of the Younger Dryas. There is no doubt that throughout high northern latitudes the great ice sheets were melting since about 18 ka. A new approach to the Younger Dryas concentrates on the route taken to the sea by the meltwater formed in northern North America (Tarasov, L & Peltier, W.R. 2005. Arctic freshwater forcing of the Younger Dryas cold reversal. *Nature*, v. **435**, p. 62-665; DOI: 10.1038/nature03617). Through their analysis of the drainage chronology of the Canadian Shield Tarasov and Pelter conclude that at the time of the onset of the Younger Dryas most flow was roughly along the present MacKenzie River valley to the Arctic Ocean. Freshening of the Arctic Ocean would escape through the narrow Fram Straits directly to the source region for NADW. It would not necessarily have been through currents, for escape of increased amounts of pack ice would have much the same effect. Central to their hypothesis are new data that relate to extraordinarily thick continental ice in the Keewatin glacial dome, that formed just to the east of modern Great Slave Lake.

Acidification of the oceans (*June 2005*)

When gases such as CO_2 and H_2S permeate through ocean water they dissolve to form weak carbonic and sulfurous acids respectively. So many organisms, plants as well as animals, incorporate carbonates into their hard parts that changes in acidity constitute an important kind of stress. The acidity of water combines with increasing pressure as water deepens to create a zone (the lysocline) in which water is undersaturated in calcium carbonate. Below the lysocline carbonate shells begin to dissolve. Deeper still is a level (the carbonate compensation depth, or CCD) below which there is no free $CaCO_3$ in the water column. Falling shelly material dissolves completely, so that deep-ocean sediments contain few if any shells other than those of silica-secreting organisms. At present the CCD is around 4 km deep. Any shift in the pH of the oceans causes the CCD either to rise or fall. The signatures of such shifts lie in the composition of ocean-floor sediments. In the deepest parts, where silica and clays dominate, layers in which carbonate shells are preserved signify a decrease in acidity (increased pH) and descent of the CCD to below the elevation of the ocean floor. On the other hand, the appearance of pure clay-silica oozes in otherwise shelly muds, where the sea floor has been well above the CCD for long periods, show that acidity increased (a drop in pH) over a period. Such anomalous sediment layers are often easy to see in cores because their colour is different from that of common sediments.

In cores from ocean depths between 2 and 4 km, the second kind of anomaly appears consistently at the level of the Palaeocene-Eocene boundary: it signifies a massive increase in acidity (Zachos, J.C. *et al*. 2005. Rapid acidification of the ocean during the Paleocene-Eocene thermal maximum. *Science*, v. 308, p. 1611-1614; DOI: 10.1126/science.1109004). Carbon-isotope measurements from the same cores also show a marked shift. The sediments are depleted in ^{13}C, which has generally been taken to indicate a huge release of methane from storage as gas hydrate in sea-floor sediment at the time of the Palaeocene-Eocene boundary. Most palaeoclimatologists consider the C-isotope “spike” to be a proxy for sudden, intense warming that resulted from methane – a more efficient ‘greenhouse’ gas than CO_2 – and the carbon dioxide produced as it was oxidized. The range of water depths where the carbonate-free layers occur enables marine geochemists to estimate the rate of acidification. In around only 10 ka the CCD rose 1.3 to 2.0 km above its current level. From the degree of acidification needed it seems that considerably more than 2×10^{12} t of carbon was released in the form of methane that eventually oxidized to CO_2, and returned to the ocean. The carbonate content of the ocean sediments rose gradually over the next 100 ka, by the end of which the former balance was restored. This information in turn gives a picture of the rate at which sudden ‘greenhouse’ events subside once their cause has stopped being produced, almost certainly by the drawdown of atmospheric CO_2 by weathering of silicate minerals exposed on the continental surface.

At the end of the Palaeocene, the effect on organisms was mainly restricted to benthic foraminifera that live in moderately deep water, which show a selective extinction. The eventual release by human activity of carbon contained in accessible fossil fuel reserves, will give a mass of carbon in ‘greenhouse’ gases of about twice that released at the Palaeocene-Eocene boundary over perhaps 300 years. Such rapid release may result in acidity that is incompatible with carbonate-secreting organisms anywhere in the oceans: the CCD will effectively be at the sea surface

Documenting the Palaeogene transition from ‘hothouse’ to ‘icehouse’ (*August 2005*)

It is well-established that the first large ice sheets that presaged descent into the oscillating climate of the Neogene formed on Antarctica about 34 Ma ago (the Eocene-Oligocene boundary). Some 21 Ma before, at the Palaeocene-Eocene boundary, global temperatures had leaped following what many believe was a massive blurt of methane previously held in cold storage in ocean-floor sediments as gas hydrate. A monstrous ‘greenhouse’ climatic system must sometime in the interim have reverted to the cooling trend begun at the outset of the Cenozoic. Defining that transformation relies on assembling and interpreting newly available, high-resolution records of climatic proxies through the Eocene and Early Oligocene (Tripati, A. *et al*. 2005. Eocene bipolar glaciation associated with global carbon cycle changes. *Nature*, v. **436**, p. 341-346; DOI: 10.1038/nature03874). Hitherto, the Eocene part of the ocean-floor sedimentary column had been poorly sampled, so that only broad trends showed.

As you might expect, the change was not a simple transition. At about 42 Ma the record of the Pacific Ocean calcite compensation depth (CCD - the depth at which carbonate remains are dissolved in the deep oceans) shows a remarkable perturbation long before the CCD dipped decisively from about 3.5 km to around 5 km at the start of the Oligocene. A close look at the oxygen isotope record of that age in a highly detailed marine sediment core shows an increase in $\delta^{18}O$ that corresponds to either some 6° of cooling or a 120 m fall in sea-level due to build-up somewhere of ice on land. Coinciding with this perturbation are shifts in the carbon-isotope record in carbonates. The authors suggest that the mid-Eocene cooling and continental glaciation that produced falling sea level triggered the weathering of shallow-water carbonates, which together with river transport increased the oceans' alkalinity. That would have increased deep-water carbonate formation enormously and accelerated the effective 'burial' of carbon from the atmosphere

Climate and the end-Permian extinction (*September 2005*)

A time in Earth history (~251 Ma) when life was all but snuffed out and from which the creatures most familiar to us eventually emerged is understandably revisited quite often. Causes ranging from impacts (no convincing evidence as yet), through flood-basalt emissions, catastrophic methane release, low atmospheric oxygen to ocean anoxia have all been proposed. Hesitantly, opinion is converging on a climatic crisis of some kind, and indeed the coincidence of both terrestrial and marine faunal and flora extinctions points to climate being the global transmitter of some cause or a coincidence of causes. After the waning of Southern Hemisphere glaciations, the late Permian was warm, even at high latitudes. Until recently, attempts at modelling the end-Permian climate have not been entirely convincing because of limitations in the models themselves. Jeffrey Kiehl and Christine Shields of the US National Center for Atmospheric Research in Colorado have assembled a model that couples land, atmosphere, oceans, sea-ice and palaeogeography for the period (Kiehl, J.T. & Shields, C.A. 2005. Climate simulation of the latest Permian: Implications for mass extinction. *Geology*, v. **33**, p. 757-760; 10.1130/G21654.1).

The critical test for the model is running it with parameters for the near-present, and it performs well. Several lines of evidence point to a much higher CO_2 level in the Permian atmosphere, so this is the main input parameter. The outcome is a world with a mean surface temperature that is 8° C higher than now. Unlike today, there was no geographic hindrance to poleward heat transport, so the high mean temperature is reflected in the summer warmth and humidity of Permian high-latitude land. The sub–tropics on the other hand were scorching (around an average summer minimum of 51° C, 15° C higher than now); a clear contributor to minimising life there. Sea-surface temperatures at high latitudes are higher in the model outcomes, this warmth extending to depths of 3 km. Surprisingly, low-latitude sea temperature emerges as much the same as now. The model also suggests that seawater was saltier than now, and that results in greater uniformity of density with depth and location: a hindrance to bottomward circulation and mixing. There would probably have been no thermohaline circulation worth speaking of. The model helps confirm the likelihood of an oxygen-free lower ocean and little transfer of nutrients. The oceans too would have been inhospitable. A shutdown of biological productivity and therefore carbon burial would have accelerated warming. So, pushing the biosphere into a mass extinction would have been inevitable. The last straw may have been the additional stress of increasing acidity from sulphur dioxide emissions from the Siberian flood basalts.

Milankovich forcing and Early Jurassic methane (*September 2005*)

Periods of environmental crisis less severe than those leading to mass extinction appear throughout the fossil record. As well as minor extinction peaks they are often signified by departures of carbon-isotope records from long-lasting norms. Such a crisis appears in the $\delta^{13}C$ record of the Early Jurassic, and is beautifully preserved in about 15 m of black shales on the North Yorkshire coast of England. Geoscientists from the Open University, UK and the University of Cologne, Germany have produced an extremely high-resolution time series of carbon-isotope data from the section (Kemp, D.B. *et al*. 2005. Astronomical pacing of methane release in the Early Jurassic period. *Nature*, v. **437**, p. 396-399; DOI: 10.1038/nature04037). The quality is sufficiently good to analyse the time series using Fourier analysis that yields the frequencies that contribute to the observed wave-like patterns in the data. Of course, the time in a stratigraphic time series is measured in metres, unless it is possible to calibrate the section by precise radiometric dating. The Yorkshire Jurassic contains only fossils and no dateable horizons, but the fine stratigraphic division based on ammonites is also widespread and calibration is possible from dates obtained elsewhere. The overwhelmingly dominant frequency in the carbon-isotope curve is 1.23 cycles m^{-1}, which represents 21 ka after the calibration of depth to time. That is the signal of precession of the equinoxes, part of the astronomical forcing bound up in Miliutin Milankovich's theory of astronomical forcing of climate.

Astronomical pacing turns up throughout the stratigraphic column, wherever sediments are suitable for time-series analysis (steady, unbroken sedimentation), so a precessional signal is no great surprise. The important feature is the profundity of the $\delta^{13}C$ excursions; a total of –7‰, largely accomplished by three abrupt shifts of –2 to –3‰. The first two coincide with bursts in extinctions. The most likely phenomenon to have produced these shifts is massive release of methane by destabilization of submarine gas hydrates. Emissions seem to have been blurting out on a regular basis as the Earth's rotational axis precessed like a gyroscope. So, the complete time period was one in which gas hydrate was unstable, probably due to overall warming. Yet something else must have triggered vast releases three times. The Lower Jurassic extinctions link in time with massive magmatism in Southern Africa and Antarctic (the Karoo-Ferrar large igneous province). Perhaps especially large volcanic events there set the stage for large precessional methane releases. An alternative view is that volcanic emissions of CO_2 gradually produced enough widespread warming for the astronomical trigger to cause breakdown of gas hydrate simultaneously over very wide areas of the ocean floor. Other explanations have been suggested for the Lower Jurassic warming and carbon-isotope excursions, such as wildfires, impacts and connections with petroleum maturation and migration. The clear cyclicity rules them out.

Photosynthesis during a 'Snowball' epoch (*October 2005*)

In Neoproterozoic sedimentary sequences evidence for low latitude glaciation crops up at two and probably several other times; so-called 'Snowball Earth' events. Opinion is divided on several aspects of these events: whether or not they truly coated the Earth in glacial ice; their influence on biological evolution; the processes that started and terminated them. From a biological standpoint, a completely ice-bound surface – both land and oceans – would have stressed organisms to the extreme. Marine life (all that there was in those times) may only have survived in a few refuges from the ice, perhaps around submarine hydrothermal vents or in ephemeral sea-ice leads and polynya. If that were so, then these frigid episodes would have created important evolutionary 'bottlenecks', from which sprang several adaptive radiations: 'Snowball' epochs may have determined the forms and genetic diversity of all later life, especially among the Eucarya, of which we are a part. Probable deep-ocean anoxia would have been particularly stressful for organisms that depend on oxygen.

The key to establishing whether or not Neoproterozoic frigid episodes did bring eucaryan life to the verge of extinction lies in the diversity of life during those periods. That is not an easy task as all life until just before the Cambrian Explosion was both soft-bodied and minute. One means of assessing diversity is to study biochemical remnants of cell processes preserved in reduced ocean sediments (Olcott, A.N. *et al*. 2005. Biomarker evidence for photosynthesis during Neoproterozoic glaciation. *Science*, v. **310**, p. 471-474; DOI: 10.1126/science.1115769). Olcott and colleagues studied black shales from Brazil whose age is within that of a frigid episode (740-700 Ma), and which contain textural evidence for abundant sea ice and low temperatures. Recovered biochemical compounds indicate considerable diversity, with a mixture of photosynthetic blue-green bacteria and eucaryan algae, with anaerobic bacteria of several types. The results indicate open water to allow photosynthesis – although it is possible for light to penetrate several metres of sea ice – together with deeper anoxic waters. Since the samples span a section almost 100 m thick, it seems this diversity persisted for a long period. However, the most that it can establish with certainty is that thin sea ice or open water did persist at the low palaeolatitude of late-Precambrian Brazil. The Neoproterozoic record has abundant, widespread black shales, and quite possibly there are others associated with evidence for glacial events. The importance of the paper lies in showing that biomarkers can be used as effectively in the Precambrian as in the Phanerozoic, and an expansion of this approach can be expected.

Yet further back in the Antarctic ice (*November 2005*)

The groundbreaking Vostok ice core from Antarctica is the deepest ever to have been drilled. It recorded 440 ka of climate and atmospheric history, but unfortunately the very depth of the ice beneath the drilling station made that the limit in time terms. Thick ice begins to deform and flow, and the lowest parts of the Vostok core were clearly scrambled by that. The European Project for Ice Coring in Antarctica (EPICA) focussed its effort on a region of the East Antarctic ice sheet (Dome Concordia) whose location may always have ensured low accumulation of snow. Hopefully that would ensure that ice thickness was not so much as to result in complex flow at depth and that a fuller record would be preserved. The idea paid off, and the Dome C core penetrates back as far as 740 ka, giving an additional

3 glacial-interglacial cycles during the early part of the 100 ka periodicity; but falling just short of the first of those major cycles that are reflected in the marine oxygen-isotope record.

Results are now starting to emerge from Dome C (Siegenthaler, U and 10 others 2005. Stable carbon cycle-climate relationship during the Late Pleistocene. *Science*, v. **310**, p. 1313-1317; DOI: 10.1126/science.1120130. Spahni, R. and 10 others 2005. Atmospheric methane and nitrous oxide of the Late Pleistocene from Antarctic ice cores. *Science*, v. **310**, p. 1317-1321; DOI: 10.1126/science.1120132). The results are high-quality, and reveal some new features. The first three cycles conform to the 100 ka signal of the very weak variation in orbital eccentricity, as expected, but show lower amplitude shifts in CO_2 and methane in air trapped in bubbles than do the later four cycles. The two 'greenhouse' gases vary in concert, and their earlier low levels match with less extreme shifts in temperature as shown by the changes in deuterium content of the ice itself. This is probably due to the transition from the previous dominance by the 40 ka pace of changing axial tilt. Nitrous oxide values, although patchy down the core, seem to have fluctuated but at much the same amplitude throughout the last 720 00 ka. Dome C has yet to be 'bottomed out' so there is a chance that the record may yet reach the 40-100 ka boundary around 900 ka ago. What is striking – and should ring alarm bells - from the results so far is that in each of the previous 7 interglacials atmospheric neither CO_2 nor methane levels came close to those of the last century. Whatever its eventual effects, anthropogenic addition to the 'greenhouse effect' is an incontrovertible fact.

See also: Brook, E.J. 2005. Tiny bubbles tell all. *Science*, v. **210**, p. 1285-7; DOI: 10.1126/science.1121535.