Climate change and palaeoclimatology

Climate change and collapse of early civilisations (*February 2006*)

About 4200 years ago early civilisations of the Old World underwent decline and collapse. Examples are the Akkadian civilisation in the upper Tigris and Euphrates basins, famed for Hammurabi's Hanging Gardens of Babylon, the Harappan of the Indus Valley (Mohenjodaro), the pharaonic Old Kingdom of Egypt and the Minoan of Crete. This period of the Early Bronze Age has been thought by some to have experienced either massive volcanism – the explosion of Santorini – or even a comet strike. Others have correlated collapses of city states with Biblical events. Whatever happened, its outcome spanned a vast area of western Asia and north-eastern Africa, so another candidate is climatic drying leading to drought and famine. That is perhaps not such a spectacular fate as near-instant environmental upheavals, but probably just as effective for societies dependant on regular agriculture production or, in the case of Crete, on wide-ranging trade.

Detecting climate change is now well established using proxy records of one kind or another, such as those based on isotopes and sedimentation changes from sea-floor sediments, flowstone (speleothem) in caves, and records in ice cores. Such time-series from the mid- to late Holocene are increasing in number, with particular interest growing in records from speleothem now that precise age sequences are possible using uranium-series dating. A flowstone record from a cave in northern Italy, has helped link other time series ranging from the North Atlantic floor, in the Middle East and East Africa (Drysdale, R. *et al*. 2006. Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. *Geology*, v. **34**, p. 101-104; DOI: 10.1130/G22103.1). A team of geochemists ad environmental scientists from Australia, Italy and the UK has shown a remarkable coincidence among these widely different records, centred on 3900-4200 b.p.. From the North Atlantic at high latitudes is an upsurge in fragments deposited by ice rafting, while mean sea-surface temperatures swung downwards. Kilimanjaro ice shows a marked peak in atmospheric dustiness. Carbonate deposition peaked in the Gulf of Oman. Finally, the Italian flowstone shows peaks in $\delta^{18}O$, $\delta^{13}C$ and the magnesium:calcium ratio of its carbonates. The conclusion is a period of climatic cooling and drying that spanned 40 degrees of latitude over a period of several hundred years. This is not the signature likely to have been associated with instantaneous catastrophes. Yet nor is it typical of the episodic climate shifts of the order of a few thousand years, which were now well known features of the last glacial period and the current interglacial. It was certainly sufficiently prolonged and large enough to have wrought havoc on early civilisations, and throughout the Old World it clearly did.

Breathing life into 'Snowball Earth' (*March 2006*)

Paul Hoffman's hypothesis of episodes, mainly in the late-Precambrian, when Earth was encapsulated in ice from pole to pole has taken repeated knocks since he first proposed it. It seems only natural that he should make the evidence and his ideas more publicly available on the Web. 'Snowball Earth' is a live and important aspect of geoscientific debate, for a whole raft of reasons, and it continually evolves. Although Hoffman does use the site as a vehicle for rebuttals to all the objections that further research has raised, it is a great deal more interesting and useful than that: a very well produced resource for anyone interested in a crucial period – the Neoproterozoic – in the evolution of life. Additionally, it helps budding geoscientists come to grips with the intellectual and experimental processes involved in major advances in knowledge and understanding. Besides which, it will save Hoffman a small fortune in air fares to have his say to live audiences!

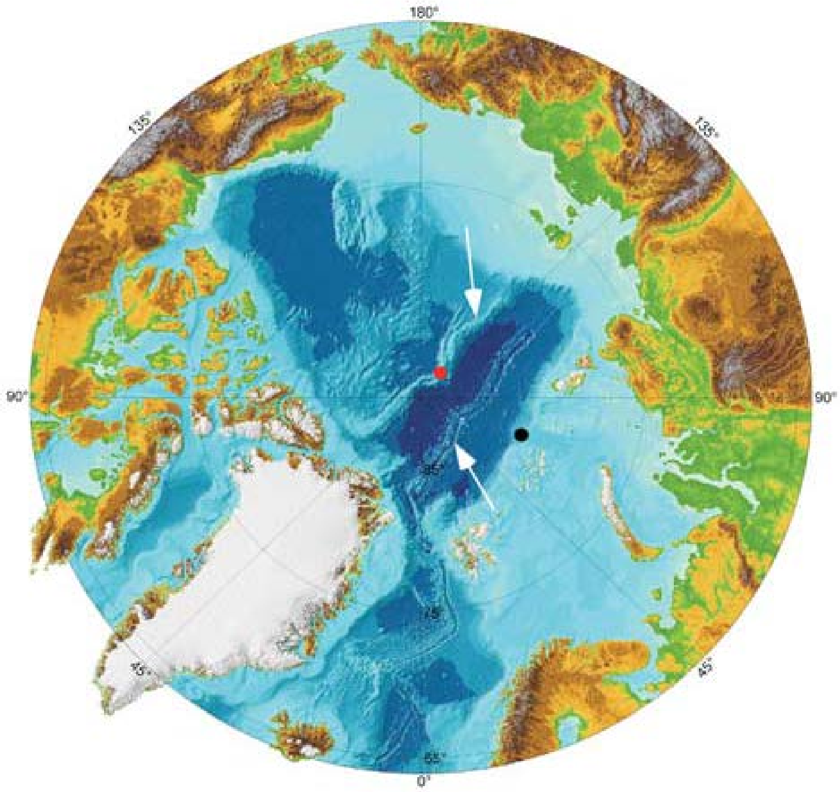
The Younger Dryas and the Flood (*June 2006*)

Between about 12.9 and 11.5 ka the progress of warming from the frigidity of the Last Glacial Maximum was rudely interrupted. For over a thousand years conditions returned to those of a mini ice age, with continental glaciers re-advancing on a large scale, an increase in aridity and a reversal of colonisation of high northern latitudes by both plants and humans. Pollen records become dominated by those of a diminutive alpine plant, the mountain avens (*Dryas octopetala*) from which the cold snap gets its name – the Younger Dryas. The pace at which cooling took place was dramatic, and glacial conditions swept in within a decade at most. The most likely scenario is failure of North Atlantic Deep Water to form, thereby shutting down the thermohaline circulation that draws the warming Gulf Stream into the Arctic Ocean off the northern cape of Norway. The reason for that was a massive and sudden freshening of surface water at high latitudes in the North Atlantic, but where the influx of fresh water came from is a puzzle. Wallace Broeker of the Lamont-Doherty Earth Observatory in New York State resurrected an earlier idea that a vast lake of meltwater in the region of the Great Lakes of North America burst down the St Lawrence Seaway, instead of quietly escaping to the Gulf of Mexico along the Missouri-Mississippi system. Broeker has recently reviewed this hypothesis (Broeker, W.S. 2006. Was the Younger Dryas triggered by a flood? *Science*, v. **312**, p. 1146-1148; DOI: 10.1126/science.1123253).

Oxygen isotope records from sediments in the Gulf of Mexico had been recording massive influx there of water depleted in ^{18}O; a sure sign that the Mississippi was carrying much of the water produced by melting of the Laurentian ice sheet. That signature stops abruptly at the outset of the Younger Dryas. The meltwater must have found another outlet, but so far its oxygen isotope signature has not been conclusively discovered. As well as the St Lawrence escape route there are three other possibilities: north-westwards along the MacKenzie River valley; beneath the great ice sheet and through Hudson Bay; and by massive break-up of the ice sheet to launch an 'armada' of icebergs that quickly melted to freshen northern Atlantic waters. One of the clearest signs that vast proglacial lakes suddenly emptied is that they carve immense channels resembling canyons, in which there is abundant evidence for extreme scouring. Examples are the 'channelled scablands' of the state of Washington, and the Minnesota River valley. The volume escaping at the start of the Younger Dryas would have been so immense that such overflow channels would be dominant features of northern North America's terrain; but there are few that fit the bill, and those that do exist are poorly constrained by radiocarbon dating. The lack of accurate dates for sediments and channels associated with the demise of the Laurentian ice sheet is the main obstacle, and surely evidence for exactly how the sudden plunge into glacial conditions was triggered will emerge sooner rather than later. One thing seems certain, the Younger Dryas was a freak event. The new ice core from Antarctica (see *Yet further back in* *the Antarctic ice* December 2005) penetrates the previous six glacial maxima and shows no sign of a similar event at their terminations.

Sedimentary evolution of the Arctic Ocean: a start is made (*June 2006*)

For the Northern Hemisphere, especially around the North Atlantic, what happens in the Arctic exerts a strong influence over climate. On the one hand, ice-cover increases the proportion of solar energy that is reflected back to space, giving a cooling effect. On the other, cooling and increasing salinity of high-latitude water at the ocean surface results in its sinking to draw in warmer waters from further south, to extend warming further north. The two are linked intricately, for sea-ice formation adds to surface waters' salinity. How and when the delicate balances arose remained poorly known while thick sea ice prevented ships penetrating to the highest possible latitudes in the Arctic Ocean, because the key to climate evolution depends on access to long core through ocean-floor sediments. Ironically, the decrease in Arctic ice cover with global warming has created greater access by icebreakers and drilling vessels. A consortium of countries around the Arctic funded a major effort to resolve the gap in knowledge through such a marine drilling programme in 2004. Results from the polar expedition have just begun to emerge (Moran, K and 36 other 2006. The Cenozoic palaeoenvironment of the Arctic Ocean. *Nature*, v. **441**, p. 601-605; DOI: 10.1038/nature04800. See also this article). The cores were taken almost at the North geographic pole on the Lomonosov Ridge, a sliver of continental crust separated from its connection with the northern Russian continental shelf when North Atlantic sea-floor spreading nosed into the Arctic about 57 Ma ago.



Topography and bathymetry of the Arctic ocean (Credit: Jakobsson *et al*. 2000. *EOS)*

The core is from sediments deposited on the Lomonosov ridge since it became detached from Russia, and is over 400 m long. Analyses are not yet complete, and the report by the IODP Arctic Coring Expedition covers the simplest parameters to determine: sediment bulk density and lithology, and micro-organisms. Nonetheless, these preliminary results provide a major surprise. Previously it was believed that frigid conditions in northern polar regions became established long after the Antarctic developed an ice cap 43 Ma ago, which matches the Cenozoic fall in atmospheric CO_2 and other evidence for lower mean global temperatures. The first glaciation in the Arctic was thought to be at 2-3 Ma, when pebbles dropped by icebergs first appear in the cores from the North Atlantic floor. In the Arctic Ocean core, such pebbles appear at much the same time as those around the Antarctic. They become widespread by 14 Ma. At the time of the Palaeocene-Eocene global warming, in response to massive methane emissions at 55 Ma, the Arctic waters were as warm as 18°C. The record is one of transition from a greenhouse world to an ice house. Surprisingly, considering the later influence of thermohaline processes that draw in warm water from lower latitudes, the earliest period is marked by fresh or at most slightly brackish waters. That was probably a result of isolation from the Atlantic and an excess of precipitation over evaporation. The early sediments record abundant carbon, then at around 14 Ma, the percentage of buried organic carbon drops dramatically to mark the start of increasing frigidity, when icebergs dropped significantly more debris in the Arctic Ocean.

Pliocene climate and a lesson for the near future? (*August 2006*)

While most geoscientists use the products of processes that operate today to judge environments of the past, climatologists do the reverse: the past is the key to the present. While the climate record of the last 2.5 Ma is a key to understanding and perhaps even predicting rapid climate shifts during glacial-interglacial periods uncontaminated by human influences, such is the extent to which greenhouse emissions have affected the current climate that we have little idea what the outcomes may be. The possibility of greenhouse warming has become higher than in any previous interglacial epoch. To get even an inkling of what that might set in motion requires looking back to warmer times than the Late Pliocene and Pleistocene, at around 3 to 5 Ma. In the Early Pliocene it is very likely that CO_2 in the atmosphere was no more than nowadays. Because the Earth's geography was little different from the way it is now and the Milankovich forcing was the same too, modelling Early Pliocene climate might seem to result in similar patterns, but it doesn't (Fedorov, A.V. *et al.* 2006. The Pliocene paradox (mechanisms for a permanent El Niño). *Science*, v. **312**, p. 1485-1489; DOI: 10.1126/science.1122666). Sea level was some 25 metres higher than it is at present and mean global temperature was an extra 3°C, and sea-surface temperatures (from the oxygen isotopes in planktonic foraminifera) were high as well. Despite much the same forcing factors as today, the Pliocene lacked large high-latitude ice caps in Arctic regions. Milankovich-related fluctuations were damped down compared with those of the Pleistocene. Both modelling and geological evidence from the Early Pliocene suggests that Earth's climate was dominated by a perpetual El Niño in the tropical oceans, because of an inability of cold water to upwell periodically along the western tropical margins of Africa and South America. Quite probably such conditions had persisted for the previous 50 Ma, despite gradual overall cooling.

Fedorov and colleagues point to very different Early Pliocene climates in several regions: Mild winters in central and north-eastern North America; droughts in Indonesia and torrential rains in western North and South America. Overall, it was a much more humid world, and since water vapour is a powerful greenhouse gas warmth and humidity were sustained despite no higher CO_2 levels than now. At about 3 Ma, ocean surface waters began to cool, with signs that the alternations associated with El Niño and La Niña in the eastern Pacific began. An explanation for this is the gradual build up of very cold water deep in the ocean as a result of winds from continents cooling ocean surface water at high latitudes and causing it to sink. Without periodic upwellings, warm surface waters and cold deep waters could not mix, so inevitably the interface became shallower. At some critical depth, this thermocline could break surface, transforming both climate patterns and those of ocean currents, eventually to end up as the present tropical climate cyclicity which is connected with other climate features of the Great Ice Age.

Fedorov *et al.* speculate that only a small descent of the ocean thermocline – a matter of a few tens of metres – could re-establish Pliocene conditions. That might occur because of continued anthropogenic warming, and the 'flip' might be as quick as a few decades to centuries.

And now, another blow for 'Snowball Earth' (*October 2006*)

The so-called Cryogenian Period of the Neoproterozoic rests on evidence for coincident glaciation at all latitudes. It has been supposed to include at least two, maybe three and perhaps more frigid 'snowball' events, each with a pattern of lower diamictites and an upper carbonate cap rock. The most widely supposed glacial epochs are the Sturtian at 712 Ma, the Marinoan at 635 Ma and the Gaskiers at 580 Ma, but Precambrian sedimentary sequences are notoriously difficult to tie down in time. Only if dateable igneous events bracket evidence for glaciation is an age truly valid. Yet the global 3-fold division depends largely on correlation of stratigraphic and carbon-isotope sequences with the odd few that are dated in an absolute time-frame. The developing field of rhenium-osmium (Re-Os) radiometric dating offers a more universal check, since it provides a means of dating highly reduced black shales, that are abundant in the Neoproterozoic. The first reported results come as a blow to the 'Snowball Earth' community (Kendall, B. *et al*. 2006. Re-Os geochronology of postglacial black shales in Australia: constraints on the timing of the 'Sturtian' glaciation. *Geology*, v. **34**, p. 729-732; DOI: 10.1130/G22775.1).

Bruce Kendall and colleagues from the Universities of Alberta, Canada and the Durham, UK have constrained some of the principal occurrences of the Sturtian event in Australia to between 643 and 657 Ma, by dating the shales which envelop the diamictites and cap carbonates. They are younger than even the widest range previously suggested for the Sturtian: either the glaciation was grossly diachronous, or this is yet another glaciation of 'Sturtian'type. The best that can be concluded is that the 'Cryogenian' was cold but glaciation shifted from place to place – a 'slushball' model?

Calibrating the deepest ice core (*November 2006*)

Although the ice that makes up the upper parts of the Greenland and Antarctic ice sheets is annually layered, for ice laid down before about 70 ka the layering disappears because of plastic deformation. Earlier ages have to be estimated from models of the deformation, and a second check is to match the data records from ice cores against those from sea floor sediments. Different processes contribute to those records: for instance, the marine record of oxygen isotopes in benthonic forams tracks the changing volume of ice locked on land, while the same record from ice cores depends on the air temperature above the ice cap. The correlation does seem to work, however. But not, it seems, for the very deepest ice recovered from beneath Antarctica (see *Yet further back in the Antarctic ice* December 2005) which extends to around 800 ka.

French scientists involved in the EPICA Dome C ice-core project have cunningly discovered a means of checking on the otherwise undateable deep Antarctic ice (Raisbeck, G.M. *et al*. 2006. ^{10}Be evidence for the Matuyama-Brunhes geomagnetic reversal in the EPICA Dome C ice core. *Nature*, v. **444**, p. 82-84; DOI: 10.1038/nature05266). The core penetrated to an estimated time that should include the most recent magnetic reversal, dated very precisely to 778$\pm$2 ka. Although the exact details of how the magnetic field behaved during this reversal, it is known that when its polarity flips the intensity of the field becomes very small. While the field is stable it is sufficiently strong to deflect charged particles, both in the Solar wind and in cosmic rays, so that less pass through the atmosphere. Cosmic rays are so energetic that they can perform isotopic transformations, one product being ^{10}Be. So if the magnetic field decreased so the proportion of ^{10}Be in the atmosphere would go up. Raisbeck and colleagues have examined the ^{10}Be record in the EPICA core in great detail. In a 10 m thick section from a depth of almost 3.2 km the isotope rises to a peak, which they interpret as the signature of the reversal. If correct, this gives a 'golden spike' against which the depth to age conversion can be refined.

Balmy shores of the Precambrian (*November 2006*)

Before the appearance of fossil organisms that could give clues to past climates the only sources of information take the form of proxies. One of the best examples might seem to be the oxygen isotope composition of carbonate rocks that relate to sea-surface temperature. In fact it isn't useful for the Precambrian because estimates of SST depend on being able to identify the shells of planktonic animals and use their $\delta^{18}O$ as a proxy. That is a pity, because limestones are common throughout the geological record and various aspects of their geochemistry have been used extensively as proxies for other crucial information, such as the relationship between their strontium isotope composition and the pace of continental weathering. Another palaeo-thermometer relies on the same temperature dependent fractionation of oxygen isotopes between seawater and the precipitation of dissolved silica to form cherts, whose $\delta^{18}O$ decreases with temperature. The trouble is that silica is notoriously prone to being remobilised and reprecipitated as pH changes in the fluids within sedimentary rocks. Some results from Precambrian cherts gave such low $\delta^{18}O$ that seawater temperature would have been tens of degrees higher than they were during the Phanerozoic, but they have been wisely suspected of having been affected by much later alteration by warmer fluids passing through cherty sequences. Now the approach has been given a boost by geochemists at the French National History Museum (Robert, F. & Chaussidon, M. 2006. A paleaotemperature curve for the Precambrian ocean based on silicon isotopes in cherts. *Nature*, v. **443**, p. 969-972; DOI: 10.1038/nature05239).

François Robert and Marc Chaussidon analysed the silicon isotopes in cherts for which oxygen isotope data are available. Since the two isotopic systems would both change, yet would behave differently during hydrothermal or metamorphic alteration, if the results correlate well both should be undisturbed. Except in samples that show the lowest $\delta^{18}O$ values (i.e. highest temperatures) there is a good correlation. That finding validates many of the O-isotope seawater temperatures, but Si isotopes fractionate during precipitation too, again in relation to temperature. So Robert and Chaussidon take Precambrian ocean temperature data to a new level with estimates based on two methods. Their results are fascinating: as well as confirming a decline from around 70°C 3.4 Ga ago to between 10 to 40°C in the Phanerozoic, the $\delta^{30}Si$ data show sharp downward 'spikes' at about 2.5 Ga and 1.8 Ga. Between about 1.5 Ga to 600 Ma ocean temperature was steady at around 20°C, so there is no sign of continually cold oceans through the period of 'Snowball Earth' events – the number of samples cannot yet resolve the individual events, but the 'Cryogenian' is an obvious target for more work. The data are also important as they hint at all kinds of possible biological outcomes for such global warmth, and explanations are definitely needed. Does the record suggest greater geothermal heating, or was it an outcome of the greenhouse effect? Will more details show periods of changing burial of organic carbon? Whatever, the Precambrian has become a stranger world to contemplate.

See also: de la Rocha, C.L. 2006. In hot water. *Nature*, v. **443**, p. 920-921; DOI: 10.1038/443920a.

Clear signs of a north-south climatic linkage (*December 2006*)

The climate records obtained from cores through the ice cap of Greenland reveal so much because they enable very fine time-resolution. That is because it snows a lot in Greenland and the ice accumulation rate is high. The down-side is that Greenland's glaciers move quickly and little more than the last glacial period (since 140 ka) is preserved. Antarctica is a great deal bigger than Greenland, and less water vapour reaches the accumulation zone of its ice cap. As a result, the record from Antarctic ice goes back much further, to 800 ka (see *Yet further back in the Antarctic ice* and *Calibrating the deepest ice core*, December 2005 and above). For most of the Antarctic cores the slow ice accumulation gives coarser time-resolution than available from Greenland. For the astronomically modulated long-term fluctuations in climate, that doesn't matter a great deal, but it poses a problem for understanding more rapid climate change that is bound up with the Earth system itself. Variations with periods of the order of a thousand years and less are products of atmospheric and oceanic circulation, in which climatologists expect different behaviour in the two hemispheres. An example is the thermohaline circulation of the North Atlantic, linked with the Gulf Stream. A widely held view is that the millennial variations in climate, which are such strong features in the record of the last glacial period, relate to periodic shutting down and restarting of the circulation, connected with changes in the salinity of the North Atlantic at high latitudes as ice sheets wax and wane. By delivering heat northwards, the North Atlantic thermohaline circulation may reduce available oceanic heat in the Southern Hemisphere: Greenland and Antarctica records should reveal whether or not there is a short-term 'see-saw' effect on climate of the two hemispheres. The different time-resolutions have prevented that hypothesis from being confirmed or refuted. November 2006 saw publication of a much more detailed Antarctic record from closer to the Southern

Ocean, in which 2500 m of ice represents 150 ka (EPICA Community Members 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, v. **444**, p. 195-198; DOI: 10.1038/nature05301).

To splice the Greenland and Antarctic records together the EPICA team used the atmospheric methane record preserved in air bubble from both, calibrated to time using annual layering back to 41 ka and flow modelling for earlier periods. Indeed, there is evidence for the predicted 'see-saw' between the hemispheres. As Greenland entered a cold stadial so Antarctica experienced a warming, and vice versa. That does not necessarily confirm a mechanism controlled by the North Atlantic thermohaline circulation: on a global scale its effect on heat transport is a lot less than processes involving atmospheric circulation. So there is a clear coupling, but also a need for a viable explanation. Interestingly, the enormous plunge back to almost full-glacial conditions in the Northern Hemisphere of the Younger Dryas (around 12 to 13 ka) still does not show up in the Antarctic record, even at a resolution of around 15 years for the new core.