Climate change and palaeoclimatology

Climate- CO_2 links since the Miocene (*January 2010*)

In *Boron isotopes and climate change*(November 2009*)* I described how the $^{11}B/^{10}B$ ratios of planktonic forams correlate with the pH of seawater, and thus with the amount of dissolved CO_2 that increases acidity. In fact the more easily analysed ratio between the boron and calcium contents of forams does the same, and for the last 800 ka correlates with the measured CO_2 content of bubbles in Antarctic ice. In turn, that correlates very well with temperatures and sea levels (Tripati, A.K. *et al*. 2009. Coupling of CO_2 and ice sheet stability over major climate transitions of the last 20 million years. *Science*, v. **326**, p. 1394-1397; DOI: 10.1126/science.1178296). Extending this approach back to 20 Ma shows that in the Middle Miocene (~10 Ma) when glacial cover began to expand atmospheric CO_2 fell from levels similar to those of the present day (387 ppm) to approximately those of the pre-industrial Holocene (~250 ppm). In the earlier Miocene from 14 to 20 Ma global mean surface temperatures were 3-6° C higher and sea level stood 40 m higher than at present. As well as this grim reminder of a possible future, the data support the general notion of a coupling between atmospheric CO_2 and global climate.

Was the Archaean blazing hot or balmy? (*January 2010*)

Silica-rich sediments, notably cherts, have been used to estimate ocean temperatures in the far off Archaean Eon. This is possible because SiO_2 and water exchange oxygen atoms as the silica mud is forming, and in doing so its two main stable isotopes (^{18}O and ^{16}O) are preferentially treated depending on water temperature. The cooler it is the more ^{18}O ends up in silica. Early Archaean cherts commonly show lower $\delta^{18}O$ values than silica-rich ocean sediments forming now; so much lower that the temperature of Palaeoarchaean seas has been judged to have been between 55 to 85° C. This does not seem very plausible, considering that without a CO_2-rich atmosphere Archaean oceans would have been frozen solid because the Sun emitted much less energy than it does now. However, such estimates have to assume that the oxygen isotopic composition of seawater at 3.5 Ga was the same as now, when in fact it is known that environmental $\delta^{18}O$ probably changes over long time periods. A way of avoiding an untestable assumption is to measure the isotopic composition of hydrogen (^1H and ^2H or D) in chert as well as that of oxygen. The cooler water is, the lower δD values are in silica that is precipitated from it. Ordinary quartz contains no hydrogen except in unstable fluid inclusions, but the way cherts form as colloidal precipitates of opal-like material locks hydrogen in the form of OH^- ions into its silica (Hren, M.T. *et al*. 2009. Oxygen and hydrogen isotope evidence for a temperate climate 3.42 billion years ago. *Nature*, v. **462**, p. 205-208; DOI: 10.1038/nature08518). Combining the two measures for 3.42 Ga cherts from the Barberton Mountain Land Archaean complex in South Africa results in a sea-surface temperature estimate of no more than 40° C.

And another oddity… (*January 2010*)

That a major climatic warming occurred at the end of the Palaeocene (55 Ma) is now undoubted, as is its probable cause by emission from the ocean floor of vast amounts of methane. Yet, oddly, the Palaeocene-Eocene Thermal Maximum (PETM) coincides with a brief geomagnetic reversal 53 ka long (Lee, Y.S. & Kodama, K. 2009. A possible link between the geomagnetic field and catastrophic climate at the Paleocene-Eocene thermal maximum. *Geology*, v. **37**, p. 1047-1050; DOI: 10.1130/G30190A.1). Both events were short, so a coincidence seems unlikely, in the authors' opinion. They suggest a connection through the massive power imparted to climatic processes by the PETM (at least a terawatt and perhaps orders of magnitude more), including the deep thermohaline circulation of the oceans that did shift during the event. Had they exceeded a threshold power for circulation of the liquid outer core they may have triggered the brief reversal, which quickly reverted to its previous magnetic polarity. Ths association is not unique, detailed magnetic studies of the K-T boundary event at 65 Ma has revealed a similar short reversal spanning the duration of the iridium peak ascribed to the Chicxulub impact. However, Chicxulub delivered a power of the order a year's solar radiation in about one second: vastly larger than the climate perturbation of the PETM. Are we seeing here a hidden signal of an extraterrestrial impact behind the methane release? Impacts are no longer as popular as they once were…

A challenge to sea-level calibration (*March 2010*)

As well as revealing the Milankovich pacemaker for past climate change, studies of oxygen isotopes from deep-water benthic foraminifera in marine sediment cores also give a guide to the height of former sea levels. That approach is based on several assumptions, of which two are central. One is that the isolation of deep-water organisms from temperature variations at the sea surface, which partly control the take up of ^{18}O by near surface plankton: well supported by the measured constancy of cold deep ocean water. The other is that oxygen is rapidly and homogeneously mixed throughout the ocean water column. The reason why good mixing is critical stems from the very purpose of measuring benthic oxygen isotopes, itself based on a sound assumption. Ice masses on land lock up a proportion of evaporated ocean water. Evaporation favours the lighter ^{16}O isotope in water molecules over the heavier, so that atmospheric water vapour has a lower $^{18}O/^{16}O$ ratio than seawater. When snow falls and turns into glacial ice that build up ice caps, surface water of the oceans becomes depleted in ^{16}O so that its $^{18}O/^{16}O$ ratio (standardised as the $\delta^{18}O$ value) increases. That makes oceanic $\delta^{18}O$ values, measured from benthic foram shells, an indirect or proxy measure of both the amount of ice locked up on land and changing sea levels: the principal quantification of past global climate change whose record goes back to the oldest preserved ocean floor (Lower Jurassic, ~205 Ma).

Modern humans eventually left Africa to colonise the rest of the world sometime before 60 Ma ago, the first reliable age of evidence for colonisation. Africa is surrounded by sea, except for the narrow strip of land into Palestine that ends up in a desert dead-end to further migrations. So, it seems likely that the exodus was across the Strait of Bab el Mandab at the outlet of the Red Sea. That passage would have become narrower and shallower as sea level fell when the Earth moved into the last glacial epoch after 117 thousand years ago, when sea-level was as high as it is today. Knowing roughly when it shallowed during the climatic ups and downs of the last glacial period is clearly important for evaluating human migration routes.

The assumption of rapid, efficient mixing of the oceans has not been thoroughly tested. In fact it is estimated that any complete turnover takes around a thousand years, so there is likely to be a significant time lag in the sea-floor record. New, independent evidence also suggests that the calibration of benthic $\delta^{18}O$ needs revision (Dorale, J.A. *et al*. 2010. Sea-level highstand 81,000 years ago in Mallorca. *Science*, v. **327**, p. 860-863; DOI: 10.1126/science.1181725). It comes from caves on the Mediterranean island of Mallorca that connect directly with the sea. Stalactites and stalagmites (collectively called speleothem) have formed in the caves, their growth being affected by flooding and drying as sea level rose and fell during the last 130 ka. At each flooding level encrustations formed around the speleothem to produce bulbous growths at different heights in the caves, which are clearly forming today at mean sea level. The researchers from the US, Mallorca, Italy and Romania dated the bulbs using the U/Th method appropriate for speleothems, and found three stages of formation: at 121, 116 and 80-82 ka. The two older encrustations are at ~2.6 m above modern sea level, bang on the oxygen isotope calibration for the end of the last interglacial. However, those formed between 80-82 ka ago – a period of warming during the overall trend to colder conditions as ice sheets grew – are about a metre above modern sea level: very different from the estimate of 10-20 m *below* based on the benthic $\delta^{18}O$ calibration.

It is too early to tell in what quandary palaeo-oceanographers will be placed by this large discrepancy. There are four main possibilities for the aberrant results. First, the Mediterranean may have stood higher than global sea level for some reason, but that seems highly unlikely as the connection through the Straits of Gibraltar is deep enough to have maintained flow even at the last glacial maximum when global sea level was around 120 m below the present. Second is that the means of calibration using raised coral reefs on tectonically rising coastlines of New Guinea and Barbados is seriously out for part of the last glacial period. Thirdly, somehow the Mallorcan crust was depressed during the last glacial period. The island is rising at about 0.2 mm yr^{-1}, which would give an uplift of 16 m since 81 ka, but that conflicts with the good match with the last highest sea level at 121 and 116 ka. Finally, the authors suggest that at 81 ka the volume of the world's ice caps was much the same as today, despite the higher-than-present $\delta^{18}O$ values in contemporary sea-floor sediments.

The Younger Dryas flood (*May 2010*)

In 2006 Wallace Broeker first suggested that the sudden interruption to global warming after the last glacial maximum by a frigid climate about 12.8 ka was due to a massive release of fresh water to the North Atlantic that shut down its thermohaline 'conveyor' (see The Younger Dryas and the Flood June 2006). He resurrected an earlier idea that a vast lake of glacial meltwater (Lake Agassiz) to the north-west 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's hypothesis was that the resulting freshening and decreased density of surface water in the North Atlantic stopped the formation of cold dense brines that sink and drag warm surface water northwards. Setting aside the notion by some enthusiastic authors that a trigger for the Younger Dryas was an exploding comet and a kind of 'nuclear winter' (see Whizz-bang view of Younger Dryas July 2007and Impact cause for Younger Dryas draws flak May 2008) Broeker's hypothesis is widely accepted. However there are few signs, if any, of a catastrophic glacial-lake outburst through the Great Lakes region and down the St Lawrence.

An alternative is that Lake Agassiz drained northwards towards the Arctic Ocean. (Since the North American ice sheet covered Hudson's Bay that could not have been the destination.) At the end of the last last full glaciation there was a corridor with relatively little glacial cover between the main ice over the Canadian Shield and that mantling the Rocky Mountains, roughly along the course of the modern Mackenzie River. That route would serve the hypothesis well, and there is clear evidence that an outburst flood followed it (Murton, J.B. *et al*. 2010. Identification of Younger Dryas outburst flood path from Lake Agassiz to the Arctic Ocean. *Nature*, v. **464**, p. 740-743; DOI: 0.1038/nature08954).

Sediments of the huge Mackenzie Delta of NW Canada contain a sharp erosion surface overlain by gravels that belie the low-energy of deposition today. Optically stimulated luminescence dating of sediment immediately below and above the erosion surface range from 13.4 (below) to 12.7 ka (above), the latter approximating the onset of frigid Younger Dryas conditions. The surface occurs all the way along the Mackenzie into its major tributary the Athabasca River. Near Fort McMurray, 20 km north of what was the northern shore of Lake Agassiz, there is a terrace composed of massive boulders. Further evidence comes from the apex of the Mackenzie delta in the form of a 25 km long, 2 km wide spillway scoured of all loose sediment and with topographic features reminiscent of the famous Channelled Scablands of Washington State in the NW USA. Numerous beach lines record the drainage of Lake Agassiz, the highest being dated at the start of the Younger Dryas and giving a clue to the volume involved in the initial outburst flood: around 9500 km^3. Dating of other features suggest that a second flooding into the Arctic Ocean occurred during the Younger Dryas around 11.5 ka, during its last stages, and a third at 9.3 ka. One effect of the Younger Dryas was a regrowth of the main ice sheet that allowed Lake Agassiz to refill periodically perhaps allowing quieter flooding events down the Mississippi and through the Great Lakes. There are no signs in the climate record of any major perturbation at 9.3 ka.

Broeker received the news graciously, commenting that a freshening of the Arctic Ocean would have been more effective at shutting down North Atlantic thermohaline circulation than a spillway down the St Lawrence, because the sites of modern day sinking of dense cold brine lie well to the north of its outlet. The only way additional water in the Arctic Ocean could escape would have been into the northernmost North Atlantic.

See also: Schiermeier, Q. & Monastersky, R. 2010. River reveals chilling tracks of ancient flood. *Nature*, v. **464**, p. 657; DOI: 10.1038/464657a · .

'Hard' Snowball Earth softens (*May 2010*)

The original hypothesis of Neoproterozoic global glacial conditions, proposed by Joe Kirschvink (California Institute of Technology) and Paul Hoffman (emeritus at Harvard) in the 1990s was that conditions became so severe that the Earth was encased in glacial- and sea ice from pole to pole. Since 2000, that 'hard' Snowball variant has become increasingly less favoured by most geoscientists (Kerr, R.A. 2010. Snowball Earth has melted back to a profound wintry mix. *Science*, v. **327**, p. 1186; DOI: 10.1126/science.327.5970.1186). However, evidence supporting low latitude glaciations continues to emerge (Macdonald, F.A. and 9 others 2010. Calibrating the Cryogenian. *Science*, v. **327**, p. 1241-1243; DOI: 10.1126/science.1183325). In the latest, diamictites of the so-called 'Sturtian' glaciation in north-western Canada are interbedded with volcanic rocks that give a very precise age of 716.5 Ma. That age happens to coincide with outpouring of the regionally massive Franklin flood basalts whose palaeomagnetism gives equatorial latitudes, the first recorded for the Sturtian glaciation: the later Marinoan glaciation (~635 Ma) provides most low-latitude evidence for Snowball conditions. The paper by Francis Macdonald and co-workers also gives detailed carbon isotope data for a continuous sedimentary record from >811 to 583 Ma.

A potential spanner in the works for the entire Snowball Earth hypothesis is the discovery of a strange anomaly concerning palaeomagnetic pole positions during latest Neoproterozoic times (Abrajevitch, A. & van der Voo, R. 2010. Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis. *Earth and Planetary Science Letters*, v. **293**, p. 164-170; DOI: 10.1126/science.1183325). Paleomagnetism from glaciogenic rocks is the lynchpin for the notion of Snowball Earth, some occurrences recording tropical latitudes. Alexandra Abrajevitch (Kochi University, Japan) and Rob van der Voo (University of Michigan) report palaeomagnetic results for igneous rocks between 600 and 550 Ma in what are now North America and Scandinavia. The data show original inclinations of the magnetic field that are both steep and shallow, indicating high and low latitudes respectively. Plotting inclination against radiometric age for what were separate continental masses in the Ediacaran Period reveals repeated rapid changes from high to low palaeolatitudes that simply cannot be accounted for by continental drift: plate tectonic rates would have to have been unaccountably fast (~45 cm yr^{-1}). To account for the abrupt shifts the authors turn not to true polar wander – due to changes in the geometry of the geomagnetic dipole – but to rapid flips in the orientation of the dipole between a coaxial and an equatorial alignment, perhaps due to dramatic changes of circulation within the liquid outer core. Familiar geomagnetic reversals normally shift the magnetic poles between roughly the geographic pole positions. Yet there are data showing that for brief periods the reversing poles do pass through equatorial latitudes but at very low magnetic field strength. In the cases from the Ediacaran the geomagnetic poles dwelt at tropical latitudes for long periods and maintained a strong field. Were such strange behaviour demonstrated earlier in the Neoproterozoic, during the Cryogenian period of supposed Snowball events, that would undermine the whole basis for the hypothesis. It seems inevitable that geophysicists will scurry to check the earlier palaeomagnetic data, analysing more igneous rocks on all continents at the narrowest possible time intervals.

Why a glacial period ends (*July 2010*)

The publicity and debate that sprang up in the 9 months after release of e-mails stolen (17 November 2009) from the University of East Anglia's Climatic Research Unit, and several debacles regarding pronouncements by the Intergovernmental Panel on Climate Change have in fact cleared the air on several purely scientific matters. Contrary to what had become the broad public conception, thanks to massive and continuous propaganda about global warming that barely mentions anything else, greenhouse gas emissions are widely revealed to be not the 'only game in town' when it comes to past changes in climate. That is very much the lesson learned by decades of study of the greatest climate change that fully modern humans have experienced: the last glacial termination when the deepest frigidity about 20 ka ago gave way to very rapid warming. A review of that enormous world event carries important lessons about what really controls climate on our world and how complex that is (Denton, G.H. *et al*. 2010. The last glacial termination. *Science*, v. **328**, p. 1652-1656; DOI: 10.1126/science.1184119).

Since the 1970s proxy data from deep-sea sediments that reveal the variation in the volume of glacial ice on land have showed how climate changes over the last 2.5 Ma are broadly correlated with the periodic astronomical effects on the amount of solar energy received by Earth (insolation), particularly that at high northern latitudes. This might suggest that glacial terminations occur when insolation reaches maxima. In fact over the last 800 ka terminations have also occurred at times of low insolation. The Milankovich signal is ubiquitous but it is not the primary driving factor for the end of glacial episodes. Nor do they tally exactly with increased CO_2 in the atmosphere, as recorded in air bubble trapped in polar ice. In fact there is a lag between the record for greenhouse gases and those for warming and cooling. The clearest correlation is between terminations and the maximum volume of land ice in each glacial epoch, towards which Denton et al. direct most attention. Since Antarctic ice has barely changed volume since the Pliocene, pulsation in land-ice volume must stem mostly from Northern Hemisphere glaciation and deglaciation. That repeatedly occurred around the North Atlantic where the main sites for ocean-water downwelling occur. At their thickest the North American and European ice sheets also had their greatest isostatic effects, bowing down the crust, and increasing ice flow towards the ocean. Time after time in each glacial build-up such a configuration became unstable so that marginal ice collapsed to produce the iceberg ‘armadas’ known as Heinrich events. Freshening of the North Atlantic by iceberg melting shut down the downwelling, thereby thermally isolating high northern latitudes to give Dansgaard-Oeschger events comprising paired coolings, or stadials, followed by suddenly warming interstadials once deep circulation restarted.

What is also emerging is that, to maintain heat balance, as each stadial developed in the North Atlantic more heat was shifted to the Southern Hemisphere. Increased downwelling of cold saline water of the Southern Ocean drove this warming to higher southern latitudes. The net observed effect is a southern reversal of sea-surface and polar air temperatures compared with those of the Northern Hemisphere, especially clear in the late stages of the last termination, including the Younger Dryas. Each warming of the south encouraged the southern oceans to emit stored CO_2 to the atmosphere, until finally sufficient to maintain global warm conditions when they arose during terminations.

Flatulence and the Younger Dryas (*July 2010*)

There is a widespread belief that the enlarging herds of domesticated ruminants, mainly cattle, goats and sheep, may have had some effect on recent climate: their enteric fermentation of cellulose generates methane, a powerful greenhouse gas. Livestock produce an estimated 80 million metric tons of methane annually, accounting for about 28% of anthropogenic methane emissions. Livestock aren’t the only methane emitting ruminants: giraffe; bison; yaks; water buffalo; deer; camels (including llamas and alpacas); and antelope. Elephants are not so efficient, but they do break wind a great deal. An adult elephant emits about half a ton of methane annually: enough to run a car 20 miles per day; on the school run for instance.

Livestock have become the dominant herbivores on the planet, but far more wild ruminants roamed the Earth during the last glacial epoch because of the much greater expanses of grasslands during cooler, more arid conditions. This was especially the case in North America, a much diminished impression being given by the vast herds of bison that were almost exterminated in the 19th century and those of caribou that still migrate across Alaska and northern Canada in their millions. The estimated ruminant population of late-Pleistocene prairies was so large that it too has been implicated in climate change during the last glacial termination (Smith, F.A. *et al*. 2010. Methane emissions from extinct megafauna. *Nature Geoscience*, v. **3**, p. 374-375; DOI: 10.1038/ngeo877), with estimated annual emissions around 10 million tons. Atmospheric methane concentrations having reached around 650 parts per billion by volume (ppbv) by 15 ka – a third of those today – the farting animals of the prairies may have made a significant contribution to post-glacial global warming. Sometime around 13 ka immigrant humans from Asia entered the scene, armed with efficient hunting weapons. By 11.5 ka, the vast herds had more or less vanished through extinction, and the 10 megaton methane emission went with them. Felisa Smith and her colleagues from the University of New Mexico, Los Alamos National National Laboratory and the Smithsonian Institution, USA, note that over the same period atmospheric methane content fell from 650 to <500 ppbv. They speculate that part of this decline may have resulted from the extinction of the North American 'megafauna' and contributed to the Younger Dryas cooling between 12.8 to 11.5 ka. If that were the case, it would have been the earliest instance of a human effect on the Earth and, opine the authors, ought to be used to mark the start of what some geoscientists propose as a new geological Epoch: the 'Anthropocene'. This parochial view surely ranks alongside that of a shower of nano-diamonds from an extraterrestrial explosion as the cause of the Younger Dryas, to the posthumous annoyance of William of Ockham (Occam).

Doubt cast on erosion and weathering theory of climate change (*July 2010*)

A seminal paper in the late 1980's by Maureen Raymo, Flip Froelich and Bill Ruddiman proposed that the uplift of mountain ranges, their erosion and associated chemical weathering helped gradually shift global climate. Their main reasoning was that rotting of feldspars by carbonic acid formed when CO_2 dissolves in rainwater locked the greenhouse gas in soil carbonates and supplied bicarbonate ions to sea water, where they would recombine with calcium and magnesium ions also released by weathering to form limestones. This process would draw down greenhouse gas levels in the atmosphere faster during episodes of major mountain building. Such carbonate burial has since been assumed to have helped the Earth's climate cool during the Cenozoic era, after the Alps, Andes and especially the Himalaya began to form. There have been many publications about the processes involved and the geochemical signature of varying erosion, such as changes in the strontium isotope composition of limestones as a proxy for that of sea water. But the real test for whether or not there have been pulses in erosion controlled by orogeny would involve measuring changes over time in sediment deposition in all the world's sedimentary basins. In a recent paper (Willenbring, J.K. & von Blanckenburg, F. 2010. Long-term stability of global erosion rates and weathering during late-Cenozoic cooling. *Nature*, v. **465**, p. 211-214; DOI: 10.1038/nature09044) published estimates of continent derived sedimentation plotted against atmospheric CO_2 derived from various proxies show two features. First, there hasn't been a truly significant decrease in CO_2 since the end of the Oligocene (23 Ma). Secondly, although sedimentation over every 5 Ma rose from about 6 x 10^{15} to 10^{16} t between the end of the Oligocene and the start of the Pliocene. Repeated glaciation over the last 5 Ma helped increase global sedimentation to 3 x 10^{16} t, but even that tripling seems not to have had much effect on atmospheric CO_2.

Willenbring and von Blanckenburg have attempted to improve the very uncertain evolution of the sedimentary record based on basin stratigraphy – despite seismic sections in many basins, costly and still rare 3-D cross sections are the only means of working out actual masses of sediment deposited through time. The authors re-examined the record of beryllium isotopes in sediments and manganese crusts from the deep-ocean floor, as a proxy for rates of weathering of continental debris. The principle behind this is the continuous production of radioactive ^{10}Be in the atmosphere by cosmic rays, and its entry into the oceans. There it mixes with stable ^{9}Be released to solution by weathering of rocks. Allowing for the decay of ^{10}Be and assuming constant rates at which it is produced, the $^{10}Be/^{9}Be$ ratio in ocean water and sediments in contact with it is a proxy for global weathering. A decrease in the ratio implies an increase in continental weathering, while decreases signify periods of slowing rock breakdown. Over the last 10 Ma, the ratio has stayed more or less constant in the Pacific and Atlantic Oceans. The obvious conclusion is that the last 10 Ma showed no pulse in weathering and that period did not follow the Raymo-Froelich-Ruddiman model. There are several explanations for the 'flat-lining' Be isotopes (Goddéris, Y. 2010. Mountains without erosion. *Nature*, v. **465**, p. 169-171; DOI: 10.1038/465169a ·), but a rethink of the significance of any link between orogeny and climate is clearly on the cards.

On the same topic, the start of Northern Hemisphere glaciations and its 30-40 Ma lead-in, Bill Ruddiman of the University of Virginia reviews a broader range of evidence (Ruddiman, W.F. 2010. A paleoclimatic enigma. *Science*, v. **328**, p. 838-839; DOI: 10.1126/science.1188292) but not that presented by Willenbring and von Blanckenburg. He concludes that little has changed by way of explanation since the late 1990s, and decreased CO_2 was the primary forcing factor. Yet his own plot of atmospheric CO_2 estimated from marine-sediment alkenones (organic compounds produced by some phytoplankton) shows little fluctuation in the mean concentration since 20 Ma, which is around that for the Pliocene-Pleistocene Great Ice Age.

Record of rising Holocene sea-level in the tropics (*November 2010*)

Areas beyond the zones of isostatic depression by ice-loading and recovery during glacial-interglacial cycles passively undergo sea-level fall and inundation. They best record the progress of Holocene ice-sheet melting and sea-level rise since 11.5 ka, especially if they are tectonically stable. The island state of Singapore, 1.5 ° north of the Equator, is a near-ideal place for study (Bird, M.I. *et al*. 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. *Geology*, v. **38**, p. 803-806; DOI: 10.1130/G31066.1). The Australian and British geoscientists analysed a core through sediments in a mangrove swamp now just below sea level. The top 14 m penetrated a uniform though laminated sequence of marine muds, calibrated to time by radiocarbon dating of mollusc shells, mainly focused on the period from 9 to 6 ka period that the global oxygen-isotope record of ice volume suggests to have been the main period of final melting after the Younger Dryas.

Sedimentation was very rapid (~1 cm y^{-1}) from 8.5 to 7.8 ka, probably as sea level rose too rapidly for the coast to be protected by mangrove growth. Then for 400 years it slackened off to ~0.1 cm y^{-1} to rise again to 0.5 cm y^{-1} by 6.5 ka. The last date is the time of the mid-Holocene sea level highstand, after which sedimentation rate soon declined to 0.05 cm y^{-1}, when mangroves became established at the site. Stable isotopes of carbon in the core ($\delta^{13}C$)

show how the relative input of marine and terrestrial (mainly mangroves) organisms shifted over the period and are a proxy for the distance to the coastline and hence sea level. From 8.5 to 6.5 ka this was erratic from a starting point about 10 m lower than nowadays, showing rapid rises and falls that culminated in a sea level in Singapore about 3 m above present during the mid-Holocene sea level highstand that slowly declined to that of the present.

The team's findings tally with evidence for the melting record of the North American ice sheet. An interesting aspect is that they also cover the period when rice cultivation in swampy areas of SE Asia got underway (~7.7 ka). Very rapid sedimentation would have encouraged development of the substrate for the highly fertile delta plains that now support the largest regional population densities on Earth. In turn they culminated in a series of early South- and East Asian civilisations based on class societies.

Antipodean glaciers confirm complementary southern Younger Dryas warming (*November 2010*)

Studies of air-temperature proxies in cores from the Antarctic ice cap show a roughly mirrored climate record to that found in the Greenland ice. While the Northern Hemisphere underwent a sudden climate collapse into almost full-glacial conditions around 12.9 ka and an equally dramatic warming around 11.7 ka, Antarctica steadily warmed over the same period to reach full interglacial conditions by 11.5. That this climatic inversion reached relatively low southern latitudes is confirmed by a record of the changing size of glaciers on mountains in New Zealand's South Island (Kaplan, M.R. and 9 others 2010. Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature*, v. **467**, p. 194-197; DOI: 10.1038/nature09313). The US-New Zealand-Norwegian-French partnership used detailed geomorphological mapping, and cosmogenic isotope studies of exposed rock fragments to show that after about 13 ka glaciers retreated by more than a kilometre in the succeeding 1500 years in contrast to the dramatic glacial advances in northern areas such as the Scottish Highlands.