Climate change and palaeoclimatology

Life sneaked through 'Snowball Earth' *(May 2000)*

The awesome magnitude of glacial epochs in the late-Precambrian from about 850 to 590 Ma was first brought to popular attention by the late Preston Cloud in his book *Oasis in Space*. More recent work than his centred on the position of the continental masses that underwent repeated glaciation at that time. One puzzle was the close association in time and place of glacigenic sediments with thick sequences of biogenic carbonates, as well as the fact that every continent preserves evidence for glaciations during this lengthy episode. Carbonates today are manufactured at tropical latitudes, but that cannot be certain for all geological time. So the key technique in checking for low-latitude ice sheets was using magnetic field evidence, in particular the inclination of remanent magnetism preserved in rocks of that age. This gives a good approximation for their latitude at the time.

Repeatedly, investigators found evidence that large Neoproterozoic ice sheets able to extend to sea level did indeed occur on continents straddling the equator at that time. That presents a major climatic problem. Ice reflects incoming solar energy extremely well - and at that time solar power was probably somewhat less than its present value. Ice at the equator implies ice everywhere and runaway cooling, so that the oceans would freeze over too. This would seem to be a situation from which there could be no thermodynamic escape, except by slow build up of volcanic carbon dioxide to give global warming by the 'greenhouse' effect. Clearly, the Earth did emerge from a 'snowball' state, but even a short period of complete ice cover would annihilate marine life forms dependent on photosynthesis. The whole of the Eucarya would quickly disappear, though bacterial forms that depended on chemical and thermal energy sources could have survived in the depths kept liquid by geothermal energy. At least some Eucarya did survive, for following the Cryogenian Period the fossil record properly begins with the Ediacaran fauna and accelerated with a vengeance during the Cambrian Explosion. Quite possibly the enormous stress placed on primitive, small Eucarya by repeated long periods of global glaciation helped accelerate the pace of evolutionary change. But that demanded at least some ice-free parts of the oceans to sustain photosynthetic life at the base of the food chain.

Geoscientists from the Texas A&M University, and the University of Toronto (Hyde, W.T. *et al*. 2000). Neoproterozoic 'snowball Earth' simulations with a coupled climate/ice-sheet model. *Nature* v. **405**, p 425-429; doi: 10.1038/35013005) have modelled the climate when Earth had its continents clustered mainly in the southern hemisphere in the late Precambrian. For the first time they build into a late-Precambrian climate model the effects of ice sheets themselves, as well as the mathematics of energy balance and general air and ocean circulation. Even with reduced solar input and no build-up of CO_2 they found that air temperatures could have been high enough to sustain a permanent belt of open water at tropical latitudes, while clustered continents were ice bound. A spin-off from this result is that isolated, ice-free continental fragments in the tropics of the time may preserve fossils of those few metazoa that did make it through the big freezes- the long sought missing ancestors for the Cambrian Explosion of life as we know it.

Milankovic forcing flawed? *(June 2000)*

Milutin Milankovic built on James Croll's notion that perturbation of Earth's astronomical behaviour is likely to cause variations in solar heating that might lie behind repeated glacial epochs. One of the most fertile discoveries in Earth science since World War 2 is that the periodicities that Milankovic calculated do seem to dominate the time-record of climate change over the last 2.5 million years, when 50 cold-warm cycles forced changes in the oxygen isotope content of fossils from deep-ocean cores. These data record the variations in long-term storage of water in continental ice, and are a near-incontrovertible 'proxy' for both varying extents of glaciation and sea levels Much the same kinds of signals also appear to turn up in time series of other kinds from sediments of a much wider range of ages. Milankovic theory now has as much support among geoscientists as Alfred Wegener's idea of drifting continents. But problematic aspects refuse to go away. Not the least of these is the conversion of depth to time in oceanic sediments from which the longest and most detailed records have emerged. An analysis of the frequencies involved in past climate change rests or falls on the accurate conversion of depths in sediment cores to time. In oceanic sediments this is by no means an easy job, because of a lack of material that can be dated precisely.

The first attempt to unscramble the complex variation in ocean cores used a few calibration points in climate time series onshore, whose shapes seemed to match those of ocean records. The most crucial of these was that for the rise in sea level at the end of the ice age before last (called Termination II) recorded in coral reefs in the Caribbean. The most widely used date for Termination II in the Caribbean is 127±6 thousand years (ka). It was from using this date as a global time correlation that the Milankovic signals of 100, 41, 23 and 19 ka periodicities popped out of the mathematical analysis. One surprise was that the match with the prediction of varying solar heating referred to the Northern rather than the Southern Hemisphere, or the planet as a whole. A great deal of later work has hung on that, and much of it has simply assumed the Northern-Hemisphere pacemaker, such as the widely used SPECMAP time scale.

Daniel Karner and Richard Muller of the University of California in Berkeley summarise the most contrary pieces of evidence for the timing of climatic change in a recent issue of *Science* (Karner, D.B. and Muller, R.A., 2000. A causality problem for Milankovitch. *Science*, **288**, p.2143-2144; DOI: 10.1126/science.288.5474.2143). Using a different dating approach the Caribbean timing of Termination II comes out at 132 ka, while for a series of coral reefs in Papua New Guinea it appears as early as 142 ka. Detailed climate changes recorded in stalactitic material from a cave in Nevada (Devils Hole) also show an 'early' Termination II. All these ages are as precise or better than the accepted 127ka date for Termination II, so Karner and Muller see a big problem. Whereas the end of the last glaciation (Termination I) is pretty well tied down to about 12 ka, and corresponds to increased solar heating in the Northern Hemisphere from the Milankovic predictions, Termination II bucks that by 5 to 10 thousand years. A theory that is only 50% believable needs a serious seeing to!

For the last four terminations, the most varied and informative data come from cores through the Antarctic ice sheet. Though that too has its problems regarding calibration of depth to time, a recent evaluation of the climate variations over the last 420 ka (Petit, J.R. *et al*., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, p. 429-436; doi: 10.1038/20859) shows significant differences between the last four terminations. Karner and Muller suggest that each glacial-interglacial cycle may have different controls, and encourage a new look at the wealth of data, unbiased by earlier ideas centring on pacing by a single, astronomical pacemaker and accepting that climate controls are multidimensional.

Another nail in the coffin for fossil fuels *(July 2000)*

The 30- or more year long debate about anthropogenic climate change resulting from the 'greenhouse' effect of carbon dioxide releases by fossil-fuel burning has grown sharper in recent years. Some specialists have cast doubt on climatologists' ability to unravel human effects on the undoubted rise in mean surface temperature over the last 150 years from underlying fluctuations that stem from natural processes. Considering the number of forcing factors, both large and small and with different periodicities, such doubts are valid, even though they may well be overemphasised in order to support continued and rising use of petroleum and coal.

The climate record for the last millennium is known to have been one of considerable change, involving a mediaeval warm period during its first half and the so-called 'Little Ice Age' from around 1600 to the mid 19th century. Even within the recent warming trend there have been climatic ups and downs in the northern hemisphere, such as the mid-20th century warm period and several documented examples of cooling associated with major volcanism than punched aerosols into the stratosphere.

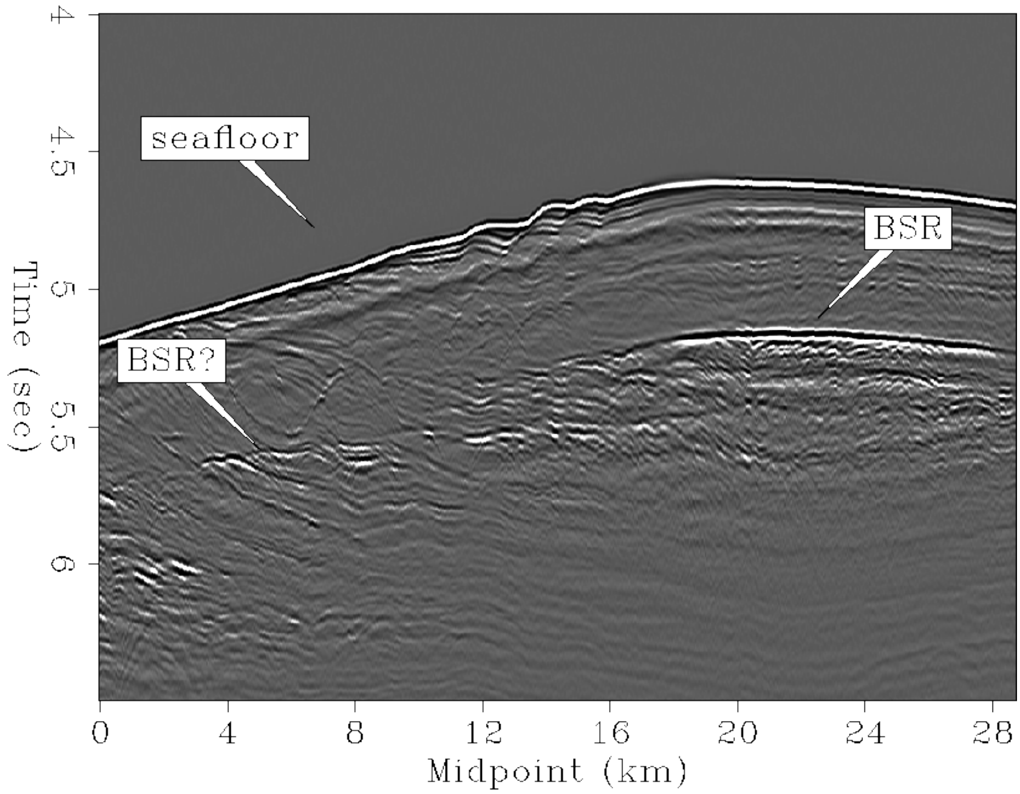
Thomas Crowley of Texas A&M University (Crowley, T.J., 2000. Causes of climate change over the past 1000 years. *Science*, v. **289**, p 270-277; DOI: 10.1126/science.289.5477.270) has attempted to isolate the known natural forcing functions and model their individual effects on mean surface temperatures in the northern hemisphere, to isolate meaningful signs of human effects from the various records temperature changes. Even charting the changes is no simple task, as most records are local to regional, rather than valid for the whole hemisphere. The most comprehensive climate data model uses proxy indicators from ice cores, tree-ring studies and coral time series, scaled to instrumental temperature records for the century from 1860-1965. Uncertainty increases backwards with time, to around ±0.3°C in year 1000 AD. This is somewhat greater than the fluctuations recorded in the temperature reconstructions that Crowley and others have derived by a complex statistical method that fits a smoothed trend to the temperature fluctuations modelled from proxy data.

The approach used in Crowley's analysis is to identify each likely, natural factor that influences energy balance in the northern hemisphere, and then to model the trends that they produced, and should continue to be producing. There are two factors that are significant in millennial to shorter timescales: influences of volcanic aerosols, as timed by ash layers in ice-sheet cores; and variations in solar output based on ^{10}Be and ^{14}C variations in ice cores and tree rings (solar radiation generates both at the top of the atmosphere). Possible anthropogenic forcing factors are numerous, including industrial aerosols and emitted gases other than the usual suspect, carbon dioxide. The end product is a temperature time series which removes the effects of all known forcing factors, except those connected with 'greenhouse' gases, from the northern-hemisphere temperature model. Until the early 19th century, this hovers close to zero variation, and then starts an upward rise to a value of about 0.75°C by now.

Crowley's modelling adds significantly to the case for a detectable economic influence on climatic warming, by showing that known natural forcings cannot account for the rising trend since the start of the Industrial Revolution. It does not prove the case, and leaves several features in recent climatic change unexplained, notably the cooling in the late 19th century. Also, this approach does not exhaust all possibilities involved in climate shifts, such as linked fluctuations in energy movement by ocean-atmosphere circulation that work to make some regions experience cooling while others warm. Such processes might respond to variations in solar-energy input by a kind of complex resonance, which remains to be looked at.

Methane hydrate - more evidence for the 'greenhouse' time bomb *(July 2000)*

Where ocean water is more than 400 metres deep and bottom temperatures fall below 1 to 2°C methane and water can freeze to form crystals of methane hydrate. These efficiently absorb more methane in a gas-solid solution, known as a clathrate. Being lighter than seawater, methane clathrates do not carpet the ocean floor, but occupy pore spaces in sediments. Under the anaerobic conditions of marine sediments, bacteria break down buried organic matter to release methane. Build up of the gas in clathrates forms distinct reflecting horizons seen on many seismic sections of marine basins. Estimates suggest that methane clathrates contain around the same amount of buried carbon as all fossil fuels lumped together. Since methane is a powerful 'greenhouse' gas when released into the atmosphere, breakdown of the clathrates is a potential mechanism for global warming.



Sub-sea floor evidence for methane hydrate accumulations shown by bottom-simulating reflectors in a seismic section – white lines that appear to cross the sedimentary layering. They represent the lower depth limit of hydrate stability, which is governed by pressure

In 1995, evidence began to emerge that 55 Ma ago, at the Palaeocene-Eocene boundary, a pulse of global warming probably stemmed from catastrophic release of methane from ocean-floor clathrates. The signs lay in the proportions of ^{12}C to ^{13}C in organic matter within marine sediments of that age. Since organisms selectively take up the light isotope of carbon, when organic matter becomes buried, seawater becomes enriched in ^{13}C. Buried carbon, both in organic molecules and in marine carbonates, takes on the isotopic signature of seawater at the time. This means that the ups and downs of carbon burial leave an imprint in the carbon-isotope record of marine sediments. When warming of deep-ocean water or a pressure release caused by a lowering of sea-level releases biogenic methane from clathrates, its high ^{12}C content quickly appears in the carbon in seawater as a whole, by oxidation to CO_2 and solution. This reduces the proportion of heavy to light carbon in both buried organic matter and marine carbonates, forming a downward 'spike' in the carbon-isotope record. Other processes can produce the same effect, such as increased release of volcanic CO_2, which is also isotopically light, or a collapse of the marine biosphere. So ^{12}C 'spikes' need to be matched with other evidence.

Co-workers from Britain and Denmark have just reported in detail on just such an excursion that took place about 183 Ma ago, during a period of massive burial of carbon in the Jurassic Period (Hesselbo, S.P. *et al*., 2000. Massive dissociation of gas hydrate during a Jurassic ocean anoxic event. *Nature*, **v. 406**, p. 392-395; doi: 10.1038/35019044). The Early Toarcian was a period where circulation in the deep ocean stopped, to give anoxic conditions, ideal for burial of dead organisms. While that lasted, important hydrocarbon-rich source rocks for petroleum reserves were laid down, and the carbon isotopes in sea water became unusually 'heavy'. Several stratigraphic sections show evidence for a ^{12}C 'spike' in the middle of this period of general ^{13}C enrichment of the oceans. Hesselbo and co-workers isotopically analysed Toarcian mudstones exposed on the Yorkshire coast in England, which contain both marine matter and fragments of wood formed in terrestrial ecosystems. Both show ^{12}C enrichment, and that means that the entire carbon cycle at the time was somehow perturbed. With no sign of massive extinction, the signature pointed either to a methane release or to hugely increased volcanism.

Although there was strong volcanic activity on Earth during the Toarcian, it came nowhere near being able to generate the anomaly. Also the 'spike' occupies at most a period of a few tens of thousand years. Only catastrophic release of methane from clathrates, equivalent to 20% of those estimated to be present today, is able to account for the anomaly. Why it happened is nor certain; it may have been a result of either increased temperature of deep-ocean water by general global warming, to which it added, or perhaps too great a release of methane by decay in organic-rich sediments to be taken in by clathrates. Another trigger, for which evidence is lacking at present, is through a comet impact in an ocean basin.

Methane hydrate layers in the oceans pose an ever-present threat today, because of their extreme sensitivity to temperature and pressure. Some scientists believe that small releases may lie behind inexplicable disappearances of ships due to the drop in bulk density of seawater frothed by bubbles. Also many areas of shallow seas are pockmarked by vents marking methane release when sea level stood lower during glacial epochs, and at least one methane spike in ice-core records can be correlated with a massive submarine landslide off western Norway.

Silica as a control over atmospheric CO_2 levels *(July 2000)*

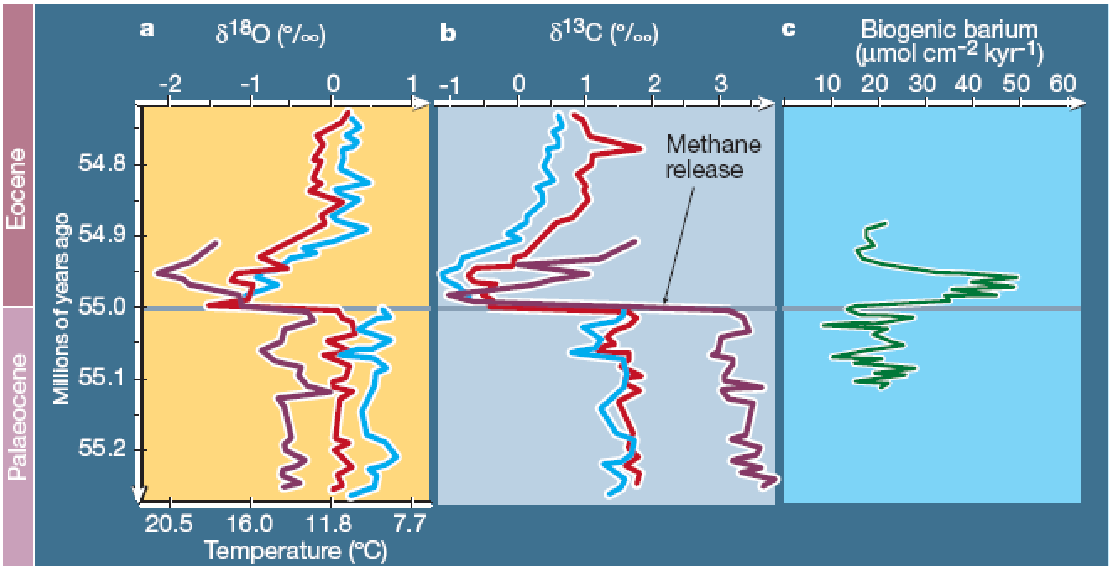
Today the oceans far from land are the equivalent of deserts, having very low biological productivity. This is not due to a lack of the main nutrients, potassium, nitrogen and phosphorus, or to too little sunlight for photosynthesis. For some time, marine specialists have suggested that the culprit is too little soluble iron - a micronutrient at the core of pigments and the enzyme RuBisCO, on which photosynthesis and the fundamental Calvin cycle depend. The halving of atmospheric CO_2 levels during glacial maxima is widely believed to reflect more efficient ocean bioproductivity and thus burial of dead organic matter. The idea that general dryness and windiness during glacial epochs delivered soluble iron to the remote ocean surface is one means of explaining this. However, it took CO_2 8 000 years to rise to pre-industrial levels after the last dusty period when ice sheets reached their maximum extent, whereas iron lingers in seawater for only a few tens of years at most. Dust carries far more silica than soluble iron, and SiO_2 resides for 15 000 years or so. This encourages the blooming of silica secreting diatoms in competition with calcium-carbonate secreting plankton. Carbonate production by cells actually generates CO_2, so less carbonate secreters relative to those producing silica shells means that tendency is offset by a greater contribution to buried carbon from dead silica secreters (Source: Tréguer, P & Pondaven, P., 2000. Silica control of carbon dioxide. *Nature*, **v. 406**, p. 358-359; doi: 10.1038/35019236)

Plankton and the end of the Palaeocene-Eocene global warming *(September 2000)*

Various geochemical signals show that the Palaeocene-Eocene boundary (at 55 Ma) was a time of global warming superimposed on the general Cainozoic cooling from the 'hothouse' of the Cretaceous Period. Some also point to an enhanced 'greenhouse' effect driven by massive methane release from gas hydrates on the sea floor. Methane, a 'greenhouse' gas in its own right, oxidizes to CO_2 in the atmosphere, transferring its carbon that eventually ends up in the shells of marine organisms. It is the carbon-isotope blip at the P-E boundary that points to methane as a source of the warming. Not only does it appear in the marine C-isotope record from foraminifera shells in cores, but also in the teeth of terrestrial mammals, which means that the carbon reservoirs of both atmosphere and seawater were globally changed. Using the magnitude of that signal allowed palaeoclimatologists to estimate the amount of methane released - about 1 500 billion tonnes. On a millennial scale, that is comparable to a rate of warming similar to that currently induced by human activities.

The P-E boundary marks the most dramatic biological changes since the mass extinction 10 million years before at the Cretaceous-Tertiary boundary. But its underlying control is sufficiently close to what is happening to climate now to form both an object lesson and a means of modelling what may happen if current emissions continue. One of the important aspects needing scrutiny is how such warming events come to an end. British and American oceanographers have taken a look at the P-E record in ocean sediment cores, and believe they have come up with an answer, at least in part (Bains, S. *et al*. 2000. Termination of global warmth at the Palaeocene/Eocene boundary through productivity feedback. *Nature*, v. **407**, p. 171-174; doi: 10.1038/35025035).

Most such studies focus on oxygen- and carbon-isotope records in the carbonate of foraminifera shells, revealing ups and downs in seawater temperature and volume of land ice, and of biological productivity and releases of 'greenhouse' gases. Unfortunately, neither isotopic record properly resolves the alternative contributions to variation. Santo Bains and colleagues add another parameter that helps resolve the influence of biological productivity in the oceans. Marine organisms, especially plankton, either precipitate barium sulphate (barite) in tiny crystals within their cells or induce its precipitation once they die and decay. Because barite is not prone to much change by later events on the sea floor, counting its crystals in marine cores is a reliable proxy for the varying abundance of plankton through time.



Variations in oxygen- and carbon isotopes and barium content of foraminifera shells at the Palaeocene-Eocene boundary. (Credit: Schmitz 2000; Fig 1

One strong possibility during major warming events is that ocean circulation becomes sluggish, perhaps stopping altogether. That slows the re-supply of nutrients to sunlit upper layers, and works to reduce photosynthetic life in the oceans. The barite record produced by Bains *et al*. shows the opposite for the P-E events. For about 40 000 years after the P-E event biogenic barite rose to more than twice its normal abundance. The ocean biosphere responded to the methane blurt by blooming. Why it did so is not yet clear, but such a spurt in drawing CO_2 into living and dead and buried tissue would work to reverse the warming event. The barite peak coincides exactly with the oxygen- and carbon-isotope records' features that signify temperature and the influence of isotopically light carbon from methane released by gas-hydrate breakdown. It might seem as if life did regulate climate in a geologically rapid manner following the P-E event, to the delight of Gaians. However, the control over biological productivity is ultimately nutrients, and life has little influence over their supply to the oceans. Among the possibilities for an essential nutrient bonanza, and increased circulation of the oceans is definitely ruled out during major warmings, are hugely increased rainfall to wash terrestrial sediments and dissolved matter into the oceans, and increased volcanism that would supply fine ash to the distant ocean surface.

Converging on an explanation for the end of a period of global warming is far from showing how this might be achieved for a warming induced by human activities. That might well prove eventually to be a life-or-death necessity for our species, bearing in mind that the P-E warming was a fatal crisis for many land mammals of the time.

See also: Schmitz, B., 2000. Plankton cooled a greenhouse. *Nature*, v. **407**, p. 143-144; doi: 10.1038/35025173.

A new regular pulse in recent climate *(September 2000)*

Gerard Bond of the Lamont-Doherty Earth Observatory at Columbia University, Palisades, New York has taken his analysis of high-frequency climatic shifts in the last glaciation into the Holocene record. Previously, Bond had tried to make sense of the sharp fluctuations of the order of a few thousand years that are seen as gravel layers in the uppermost levels of sea-floor cores and in the oxygen isotope records of cores through the Greenlandic and Antarctic ice sheets. The first signs of short ups and downs in climate were the coarse layers first found by Hartmut Heinrich in the glacial part of the sea-floor record. Heinrich ascribed them to periodic releases of iceberg armadas as the ice sheets of the last glaciation became unstable. Bond's latest work also focuses on Heinrich events, but he has used specific lithologies as markers rather than merely grain-size variations. In particular, hematite-stained quartzo-feldspathic materials seem likely to have come from altered rocks in east Greenland and Svalbard, far distant from the drill sites whose cores he has examined. The proportion of reddish grains varies systematically in the cores, some layers coinciding with Heinrich events, but there are many more. The layers appear roughly every 1500 years. This periodicity coincides with cycles of dust blown from the Sahara to form layers in cores from the west African coast, so whatever the pulses represent, they are global signals.

Interestingly, the cycles show little sign of change in the period after the melt back that signified the beginning of the Holocene interglacial. Behind the long-term climatic shifts in glacial- and interglacial episodes, that coincide with the 100, 41, 23 and 19 thousand year fluctuations in solar warming of the northern hemisphere, some other process must be put-putting in the background. The 1500 year cycles may stem from processes that shift heat in the oceans and atmosphere. A likely candidate is the production of deep currents by sea-ice formation in the northern North Atlantic. However, detailed calculations of tides suggest a similar pacing that might change the mixing of surface and deep water in the ocean conveyor system.

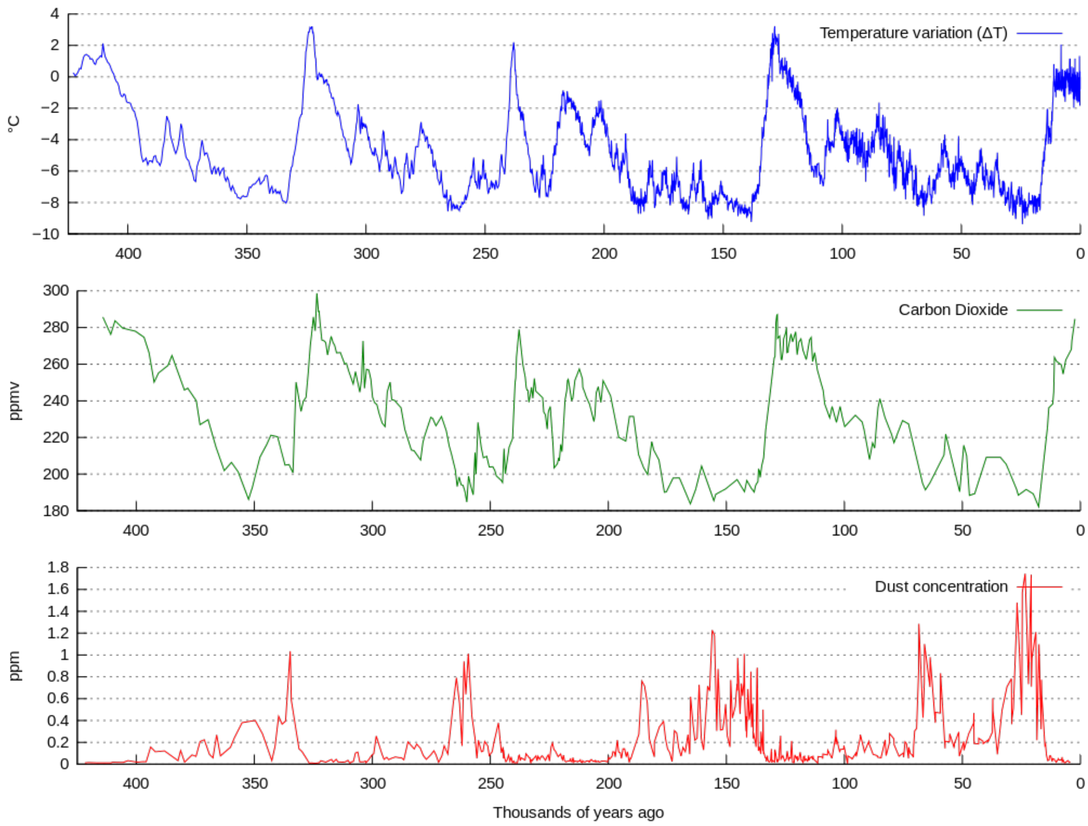
Whatever the driving force, this periodicity strikes a chord with emerging details of Holocene climate changes from lake-sediments studies and the historic record. One such recent cooling pulse that might have delivered icebergs to mid-latitudes in the North Atlantic was the Little Ice Age that peaked in the 17th century that saw prolonged stresses on the population of Europe, and major political changes that resulted from such events as the Peasants' Revolt and repeated famines.

Source: Pearce, F. 2000. Feel the pulse. *New Scientist*, 2 September 2000, p. 30-33.

Ups and downs of the "greenhouse" effect *(October 2000)*

Several gases have the property of absorbing radiation in the wavelength range emitted by the Earth because of its surface temperature, including methane as well as carbon dioxide, the usual culprit. By doing so, they delay the escape of thermal energy through the atmosphere to outer space and give the Earth a higher surface temperature than it would have if they were not present. Because methane oxidizes to CO_2 more rapidly than the latter gas's recycling time, a record of atmospheric carbon dioxide is the best guide to fluctuations in the "greenhouse" effect through the past glacial-interglacial cycles. Bubbles in cores through the ice sheets of Greenland and Antarctica trapped air at the time when snow converted to ice within a few decades after it fell in Polar Regions.

The publication of data of all kinds from the ice-core drilled beneath the Vostok camp in Antarctica opened up 420 000 years worth of atmospheric composition shifts. Daniel Sigman and Edward Boyle, of Princeton University and MIT, Massachusetts, review all the bio-geochemical factors that might have contributed to the CO_2 time series for the last 4 major climate cycles (Sigman, D. M. & Boyle, E.A. 2000. Glacial/interglacial variations in atmospheric carbon dioxide. *Nature*, v. **407**, p. 859-869; doi: 10.1038/35038000).



Temperature, atmospheric CO_2 and dust records from the 420 ka long Vostok ice core (credit: NOAA)

While work continues to fully grasp this climate forcing function, Sigman and Boyle argue convincingly that the overwhelmingly dominant influence on it is the combined biological and physical carbon "pump" of the ocean around Antarctica.

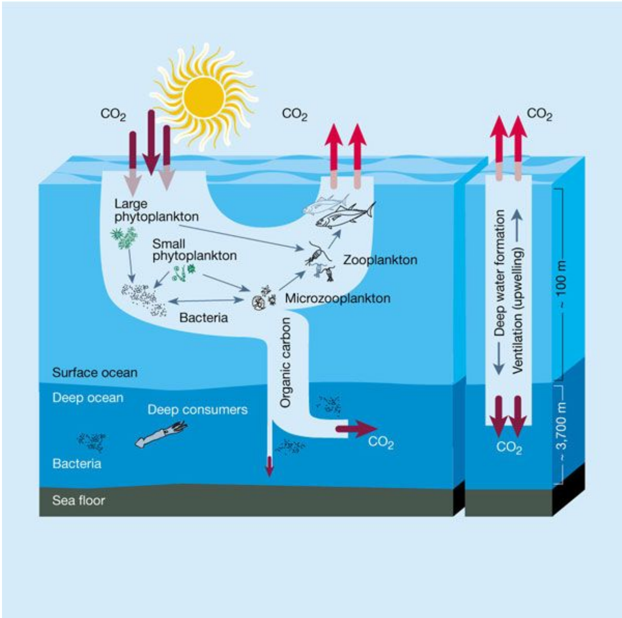
Palaeoclimate news from the South *(October 2000)*

Increasingly, evidence of many kinds points to a dominant influence on climatic ups and down through the last 2.5 Ma by processes in the northern hemisphere. Empirically, at least, the global-climate time series seems to show patterns that closely resemble Milankovic's predictions of varying insolation at high northern latitudes. For millennial-scale fluctuations, such as Heinrich events and the Dansgaard-Oeschger cycles in ocean and ice-sheet cores respectively, the focus is on changes in deep-water formation in the North Atlantic. The South cannot be set aside, however, and there are two important issues that crop up in October's publications. One is the extent to which climatic events in the southern hemisphere tracked those in the North, and the other is the role of the southern oceans in the global carbon cycle that underpins the climate-related fluctuations in atmospheric CO_2 concentrations.

Both the Greenlandic and Antarctic ice cores show synchronicity of CO_2 trapped in air bubbles with the records of local air temperature and global land-ice volume, going back over 400 ka in Antarctica. With more or less constant additions from volcanism, the ups and downs of the primary "greenhouse" gas have to be mediated by removal of carbon in one form or another from the ocean-atmosphere system through the agency of biological processes. Just what process, where it is most active and the controls underlying it form a topic of continual discussion and research. One possibility is variation in the biological productivity of the open oceans, coupled with removal of carbon from the ocean-atmosphere interface.

In terms of size and potential, the Southern Ocean is overwhelmingly the most likely candidate for a control. It is today the largest repository of unused nutrients in surface waters (by comparison with its potential for supporting phytoplankton it is a "wet" desert), but also a major source of deep-water formation that could sequester carbon from the surface environment. The late John Martin suggested that the main control over ocean productivity is soluble iron, currently at low concentrations far from land. The first realistic experiment to verify this involved "seeding" a small area of the equatorial Pacific with iron sulphate in 1995. Sure enough, that provoked a short-lived bloom of microscopic marine plants and local changes in dissolved CO_2, but a boost in productivity at low latitudes is unlikely to lead to carbon removal from the surface part of the C-cycle.

Eighteen months ago, a multinational team of 35 ocean scientists conducted a similar experiment off Antarctica at 60°S (Boyd, P.W. *et al*. 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature*, v. **407**, p. 695-702. See also: Chisholm, S.W. 2000. Stirring times in the Southern Ocean. *Nature*, v. **407**, p. 685-687; doi: 10.1038/35037696). Once again bio-productivity soared by three times, and an input of 9 t of ferrous sulphate into about 50 km^2 of ocean triggered an estimated 600 to 3000 t of extra algal carbon production. The "bloom" lasted for at least 6 weeks, being transformed into a swirling ribbon 150 km long. But it did not seem to be absorbed into deep water, merely mixing at the surface. In principle, iron dissolved from dust blown far from land during cold, dry episodes *might* have drawn down CO_2 levels, but it is still uncertain. Yet the dust records trapped in ice cores do show a pronounced negative correlation with both CO_2 and climate proxies.



The marine carbon 'pump'

Millennial-scale climate shifts are best known from the area around the North Atlantic. The most recent of these, and the most dramatic, was a sudden reversal from the warming trend out of the last glacial maximum around 13 ka ago, which lasted around 1800 years. This is recorded in many ways everywhere around the North Atlantic, and takes the name Younger Dryas (YD) from the associated increase in sediment cores of pollen of the cold-resistant mountain avens (*Dryas octopetala*). For some years there have been reports of a YD signal in climate records from the southern hemisphere, and some suggesting it was not felt there at all, the most detailed counter-evidence being the lack of the YD signal in Antarctic ice cores (ascribed by some to climatic inertia of the ice-bound continent).

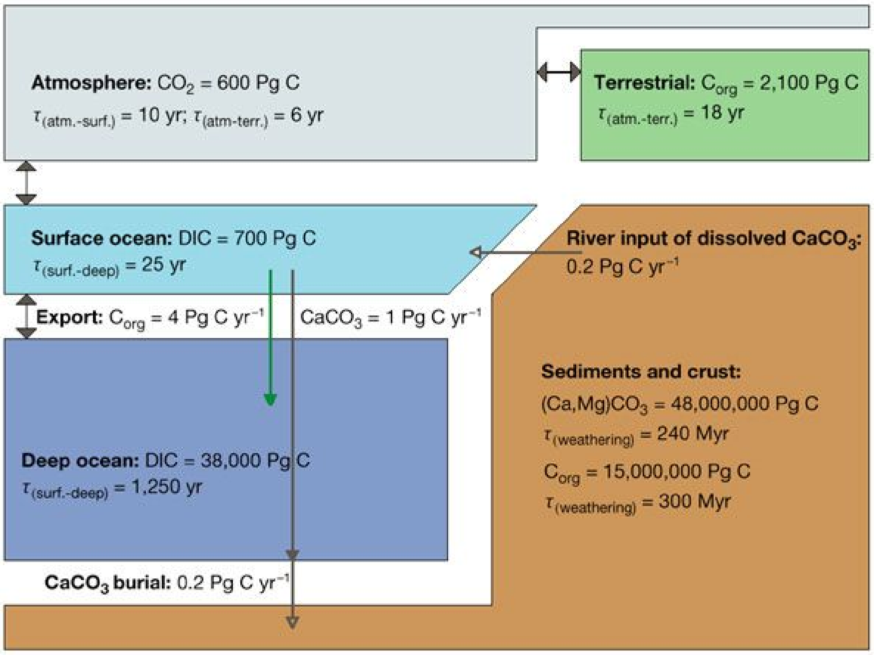
The YD interrupted warming and wetting in the lead-up to the Holocene interglacial, so its signal ought to be easy to verify or rule out, simply because no later glacial advances have obliterated suitable investigation sites and many lakes at high altitudes and latitudes formed about that time. The problem for southern-hemisphere work has been a lack of precise dates. Southern Chile proves to be an excellent place to check, because lakes there go back further and contain evidence for many glacial advances and retreats (Bennett, K.D. *et al*. 2000. The last glacial-Holocene transition in Southern Chile. *Science*, v. **290**, p, 325-328; doi: 10.1126/science.290.5490.325). Moreover, the sediment cores provide sufficient high-precision dates to construct a believably detailed time scale. Bennett and co-workers show that during the YD Chilean glaciers were retreating rather than advancing. That seems to knock the idea of "teleconnections" spanning both hemispheres for this particularly dramatic event, although its signal extends to the north Pacific. Like the mountain avens, however, disputing palaeoclimatologists are a hardy lot. It could be that the site of Bennett and colleagues work was far from a boundary between pollen-shedding species that was sensitive to climate change, despite the excellence of their record (see also Rodbell, D.T. 2000. The Younger Dryas: cold, cold everywhere? *Science*, v. **290**, p. 285-286; DOI: 10.1126/science.290.5490.285).

No escape from global warming? *(October 2000)*

Palaeoclimatology is well-funded because it is believed to shed light on the likely consequences of anthropogenic warming caused by CO_2 emissions, and perhaps even technical solutions that allow us to continue burning fossil fuels. There is no doubt that throwing money at the range of associated phenomena and data has produced many astonishing findings and connections for the last 2.5 Ma. There is now sufficient high-quality data to reviewing them in their proper context; that of the climatic aspect of the "human condition". That is the task that yet another multinational group of scientists set themselves at an International Biosphere-Geosphere Programme (IBGP) workshop at the Royal Swedish Academy of Science in November 1999 (Falkowski, P. and 16 others 2000. The global carbon cycle: a test of our knowledge of earth as a system. *Science*, v. **290**, p. 291-296; DOI: 10.1126/science.290.5490.291).

The workshop used two generalized outcomes of many years of work on Antarctic ice cores: the variation over more than 400 ka of CO_2 in trapped air bubbles with temperature shifts; the frequencies and amplitudes of changes in atmospheric CO_2. They compare these with human effects over the last 200 years. A great deal of discussion and qualification surrounds the workshop's conclusions, but they are stark and simple. Anthropogenic change falls way outside that induced by natural processes (whatever they are), and its period bears no relationship to those involved in short- to long term processes. Despite the seeming attraction of technical fixes, such as boosting ocean productivity and the deep-water carbon sink (above), and intervention in terrestrial plant processes to increase CO_2 sequestration from the atmosphere, both face the likelihood of weakening natural feedbacks due to the massive change that has taken place. Indeed, the consequences of strategies of these kinds aimed at mitigating climate change cannot be known in advance. This grim conclusion stems from the fact that no matter how well we get to know the climate system of the past, it is no longer what it was. Even a complete halt to all anthropogenic emissions now cannot reverse the trend in the short to medium term.

The group suggests Earth's entry into a new Epoch (the Anthropocene) of uncertainty, but brimming with growing knowledge. To them, this seeming paradox must not be "used as an excuse to postpone prudent policy decisions based on the best information available at the time". They also highlight the disciplinary compartmentalization of research that hinders a "proper" understanding of the Earth system. I suppose what they are getting at is the continuing ethos of Descartes' 400-year old reductionism in science, yet surely their call for a "systems approach" is merely dressing up reductionist empiricism in a more complicated guise; hurling yet more intricate maths at the problem. That is indeed the goal of climate modelling and has been for well over a decade. Perhaps the solution lies not in descriptive retrospection by scientists and in "policy", but with society as a whole that now begins to confront the mismatch between several thousand years of human activity divided from the rest of the world.



Simple view of the pre-industrial carbon cycle (Credit: Sigman & Boyle, 2000; Fig. 1)

Daniel Sigman and Edward Boyle, of Princeton University and MIT, USA, usefully review the whole issue of varying CO_2 through the 420 ka Antarctic ice-core record, together with its environmental buffering (Sigman, D.M. & Boyle, E.A. 2000. Glacial/interglacial variations in atmospheric carbon dioxide. *Nature*, v. **407**, p. 859-869; doi: 10.1038/35038000). Their article helps see the views of Falkowski *et al*. from a broad and detailed context, and links to *Palaeoclimate news from the South* (above), because Sigman and Boyle conclude that while the pacing of climate change tracks the combined effects of orbital processes on solar energy input at high northern latitudes the "greenhouse" effect changes because of biological and physical processes in the Southern Ocean that surrounds Antarctica.

The nudge of climatic noise *(October 2000)*

The emergence of a signal in the climate shifts through the last ice age and the Holocene with a roughly 1 000 to 1 500 year period (see Earth Pages Archive, *A new regular pulse in recent climate*, September 2000) finds no link with processes linked to Earth's orbital behaviour. It must be generated within the Earth system itself. That being said, there is a lot of debate over what precisely *is* involved. It's safe to say that debate will continue.

However, another factor might well be involved; one that is as much to do with statistics as with phenomena with sufficient power to flip climate patterns. Random noise is everywhere in nature. If strong enough at a critical time, such stochastic noise might resonate with an otherwise weak, periodic phenomenon to give it sufficient push that it shows up in a climate change. Let's say that there is some weak pulsation that bears on climate - not really known with certainty, but having a 1 500 year period. If resonance with noise was involved, we might expect to see 1 500, 3 000, 4 500 year periods in the climate record (1-, 2- and 3-cycle shifts), with the first more common than the last two - that is how the statistics should work. The fact that short-term climate pulses (the stadial-interstadial events) cluster around 1 000 to 1 500 years might indicate that random noise is implicated.

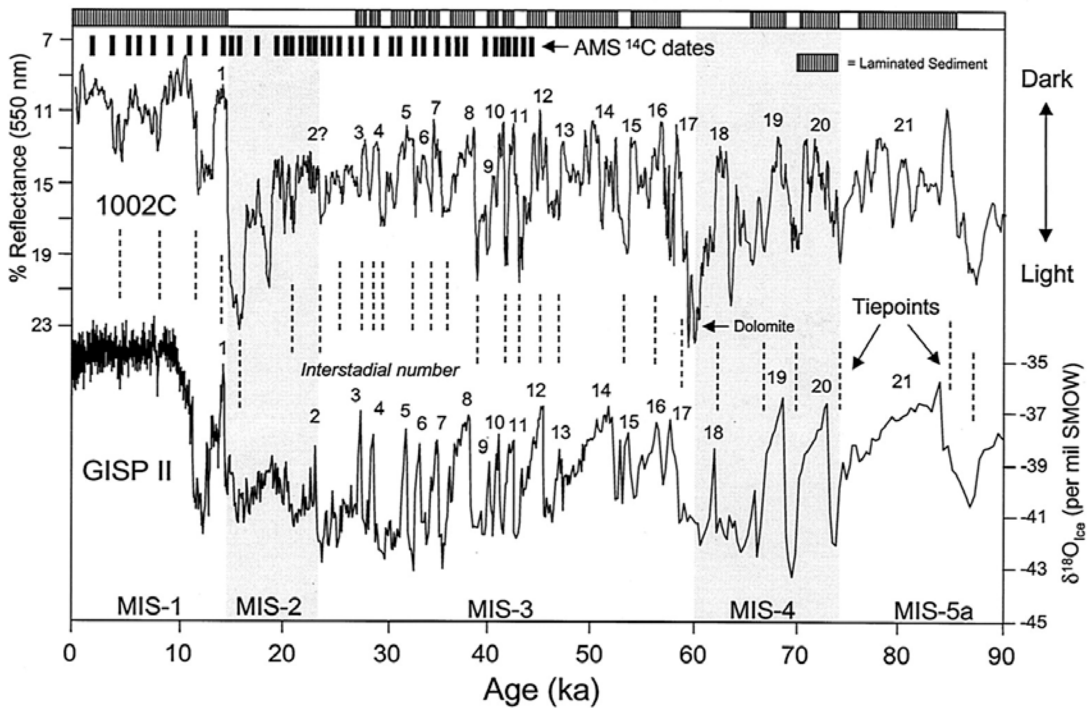
However, only the last 120 000 years of climate data have sufficient precision for such statistical analyses, so it might be fortuitous.

The same nudge of randon climatic noise has also been called on to explain the jump from a roughly 41 000 year cyclicity to the present one of 100 000 years about 700 000 years ago. The first correlates with the period of changes in the Earth's axial tilt, and the second with changes in the eccentricity of its elliptical orbit. The effect of orbital variations on the energy received from the Sun is so very small that it cannot have much of an effect on climate by itself, but changes related to axial tilt are ten times bigger. The change in behaviour seven ice ages ago is therefore hard to explain, without the nudge of noise.

Source: Kerr, R.A. 2000. Does a climate clock get a noisy boost. *Science*, v. **290**, p. 697-698; DOI: 10.1126/science.290.5492.697.

(November 2000)

The Cariaco Basin off Venezuela lies in an area that is sensitive to climate change and has been for at least the last 90 thousand years. As the trade winds change with the seasonal migration of the Intertropical Convergence Zone (ITCZ), cold, nutrient-rich waters well up along the coast of northern Venezuela. Biological productivity waxes and wanes on an annual rhythm, as do sediments transported into the basin by the great rivers of this part of South America – shifts of the ITCZ also impose annual wet and dry seasons over land. This cyclicity seems to have functioned since at least 90 ka ago, and drill cores from the Cariaco trench are dateable at the annual level because of the colour banding of seasonal sediments (Peterson, L.C. *et al*. 2000. Rapid changes in the hydrological cycle of the tropical Atlantic during the last glacial. *Science*, v. **290**, p. 1947-1951; DOI: 10.1126/science.290.5498.1947).



Variations in colour reflectance of Carioco Basin seafloor sediments (top) compared with those of $\delta^{18}O$ in the Antarctic GISP II Ice core (bottom) the numbers above which refer to marine isotope stages recognised in sea-floor sediments (credit: Peteron *et al*. 2000; Fig. 1)

Matching the varying thicknesses of colour bands beneath the Cariaco Basin to the high-latitude climate record preserved in Greenlandic ice-cores shows a remarkable correlation. Warming (interstadials) over Greenland correspond to periods of increased rainfall and ocean bio-productivity (the layers are thicker) off Venezuela. Peterson and his co-workers believe that this could signify periods of greater transport of water vapour from the Atlantic to the Pacific. That would increase the salinity of the Atlantic. Working through to high latitudes, saltier surface water would more easily become dense cold brine once sea ice had been frozen from it. That would enhance the thermohaline deep circulation of the North Atlantic, so that warm, tropical waters might be dragged further to the north during interstadials, in the manner of today's Gulf Stream. It is hard to see how just melting ice sheets during interstadials could do that; in fact that would encourage a further reduction of deep circulation. So, a tropical connection seems plausible. However, interstadials stopped extremely rapidly, repeatedly plunging high latitudes into full glacial, or stadial conditions. That may well have been an outcome of all the fresh water from melting glaciers acting to dilute surface waters' saltiness, and thereby shutting down thermohaline processes.

The annual precision of sediment cores from the Cariaco Basin carries a bonus, by helping better to calibrate ^{14}C dating. Radiocarbon dates have long been known not to correspond predictably to calendar years. For instance, dates from around 11 ka ago, the time of the last major glacial advance (the Younger Dryas) show a mismatch of about a thousand years between dates based on counting tree rings and annual ice layers (exact calendar years), and those provided by ^{14}C dating of carbon-rich samples. The reason for this is partly fluctuations in the production of ^{14}C by bombardment of nitrogen atoms in the stratosphere by cosmic radiation and the solar wind. The Cariaco Basin layering extends calendar dating at least 5 000 years further back, into the period when deglaciation accelerated as the Earth's climate emerged from the last glacial maximum (Hughen, K.A. *et al*., 2000. Synchronous radiocarbon and climate shifts during the last glaciation. *Science*, v. **290**, p. 1951-1954; DOI: 10.1126/science.290.5498.1951). That helps to evaluate shifting rates of ^{14}C production over this part of the core (maybe related to varying solar output because they match shifts in ^{10}Be, also produced by upper atmosphere processes), and to add meaning to radiocarbon dates from it. However, not all the shifts in ^{14}C can be due to solar fluctuations, and it is clear that the largest, during the Younger Dryas event, stemmed from increased carbon preservation on the ocean floor, that removes all isotopes of such carbon from the atmosphere and upper ocean. This supports the notion that the Younger Dryas, and perhaps all the stadial-interstadial events of the last 90 ka stem from changes in ocean processes.