Climate change and palaeoclimatology

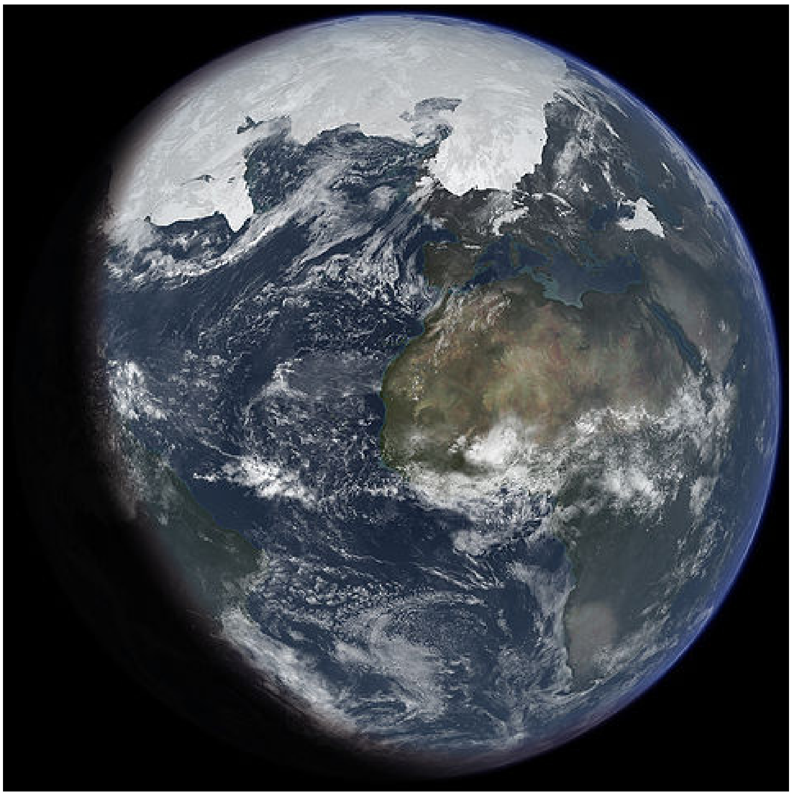
Carbon emissions: It's an ill wind… (*January 2016*)

The original saying emerged in Shakespeare's Henry IV Part 2 (Act 5, Scene 3) during a jocular exchange when Ancient Pistol brings news from Court to Sir John Falstaff and other old codgers at dinner in Gloucestershire. Falstaff: 'What wind blew you hither, Pistol?' Pistol: 'Not the ill wind which blows no man to good'. In the present context it seems anthropogenic CO_2 emissions have staved off the otherwise inevitable launch of another glacial epoch. Climate-change deniers will no doubt pounce on this in the manner of a leopard seizing a tasty young monkey.

Penny Ice Cap on Baffin Island (Credit: Ansgar Walk)

Climatologists at the Institute for Climate Impact Research in Potsdam, Germany, Potsdam University and the Santa Fe Institute in New Mexico, USA set out to develop a means for predicting the onset of ice ages (Ganopolski, A. *et al*. 2016. Critical insolation-CO_2 relation for diagnosing past and future glacial inception. *Nature*, v. **529**, p. 200-203; DOI: 10.1038/nature16494) Many researchers have concluded from the oxygen isotope data in marine sediments, which track changes in the volume of glacial ice on land, that the end of previous interglacial periods may be attributed to inception of prolonged climatic cooling due to reduction of summer solar heating at high northern latitudes. This conclusion stems from Milanković's predictions from the Earth's astronomically controlled orbital parameters and fits most of the previous interglacial to glacial transitions. But summer insolation at 65°N is now more or less at one of these minima, with no signs of drastic global cooling; rather the opposite, as part of 7 thousand years of constant global sea level during the Holocene interglacial.

The latest supercomputer model of the Earth System (CLIMBER-2) has successfully 'predicted' the last eight ice ages from astronomical and other data derived from a variety of climate proxies. It also forecasts the next to have already begun, if atmospheric CO_2 concentration was 240 parts per million; the level during earlier interglacials most similar to that in which we live. But the pre-industrial level was 280 ppm and the model suggests that small difference would have put off the return of huge ice caps in the Northern Hemisphere for another 50 thousand years – partly because the present insolation minimum is not deep enough to launch a new ice age with that CO_2 concentration – making the Holocene likely to be by far the longest interglacial since ice-age cycles began about 2.5 Ma ago. Based on current, industrially contaminated CO_2 levels and a rapid curtailment of carbon emissions the model suggests no return to full glacial conditions within the next 100 ka and possibly longer; a consequence of the sluggishness of natural processes that draw-down CO_2 from the atmosphere.



Simulation of the Earth at a glacial maximum. (Credit: Wikipedia)

So, does this indicate that unwittingly the Industrial Revolution and subsequent growth in the use of fossil fuels tipped the balance away from global cooling that would eventually have made vast tracts of both hemispheres uninhabitable? At first sight, that's the way it looks. But the atmospheric carbon content of the 17th century would have resulted in much the same long drawn out Holocene interglacial; an unprecedented skipping of an ice age in the period covering most of the history of human evolution. This raises a question first posed by Bill Ruddiman in 2003: did human agriculture and associated CO_2 emission begin the destabilisation of the Earth system shortly after Holocene warming and human ingenuity about 10 thousand years ago made farming and herding possible?

But, consider this, the CLIMBER-2 Earth System model is said to be one of 'intermediate complexity' which is shorthand for one that relies on the ages-old scientific method of reductionism or basing each modelled scenario on modifying one parameter at a time. Moreover, for many parameters of the Earth's climate system – clouds, dust, the cooling effect of increased winter precipitation as snow, and much else – scientists are pretty much in the dark (Crucifix, M. 2016. Earth's narrow escape from a big freeze. *Nature*, v. **529**, p. 162-163; DOI: 10.1038/529162a). Indeed it is still not certain whether CO_2 levels have a naturally active or passive role in glacial-interglacial cycles, or something more complex than the simple cause-effect paradigm that still dominates much of science.

Focus on glaciation…and avoid physics envy (*February 2016*)

About 1.3 billion years ago two small black holes, each weighing in at about 30 solar masses, ran into one another and fused. At that time Earthly life forms had neither mouths nor anuses, nor even a nervous system, and they were not much bigger than a sand grain. The distant collision involved rapid acceleration of considerable masses. A century ago Albert Einstein predicted that the movement of any matter in the universe should perturb space-time in a wave-like form that travels at the same speed as light. Well, he was right for, at 9:50:45 universal time on 14 September 2015, four exquisitely engineered mirrors deployed in the two set-ups of a Laser Interferometer Gravitational-Wave Observatory (LIGO) in Louisiana and Washington states in the US minutely shuddered, first in the Deep South and 0.007 seconds later in the Pacific Northwest. The signal lasted 0.25 seconds and, when rendered as sound, comprised a sort of chirrup starting at 35 Hz and rising to 250 Hz before an abrupt end. Five months later, after silent, internationally shared theoretical verification, the story was released to the back slapping, stamping and pawing the air that we have come to expect from clever, ambitious and persuasive people who have spent a great deal of our money and have something to show for it. So now we know that the universe is probably throbbing – albeit very, very, very quietly – with gravitational waves generated by every single motion that has taken place in the whole of 'recorded' history since the Big Bang. Indeed, it is claimed, LIGO-like machines may one day detect the big wave itself if, that is, it hasn't already passed through the solar system. Recall, 13.7 billion years ago the Big Bang didn't take much longer than this comparatively mundane collision at 1.3 Ga . Physicists are going to have a lot to ponder on now they have a lever to get yet greater funds. To put all this in perspective, the detected chirrup from two colliding black holes had been travelling for 1.3 Ga, and so too must the actual place in the universe where it took place: I guess we will never know where it is now or what damage or otherwise may have been visited upon planetary systems in its vicinity, if indeed it had even the slightest recognisable geological or ecological consequence.

So, onto the mundane world of glaciology and climate change.

Tibet is the third greatest repository of glacial ice on the surface of the Earth's continents. It is the focus of the planet's greatest climatic system, the South Asian Monsoon. While much of the Plateau hasn't borne glaciers continuously throughout even the last glacial cycle, it is becoming clear that its western margin has remained cold enough to retain ice throughout an even longer period. In the Kunlun Range is a 200 km^2 ice cap known as the Guliya. At the start of detailed glacial stratigraphic ventures in 1990s, focused mainly on Greenland and Antarctica, analysis of a core from the Guliya ice cap yielded dates extending back to 130 ka, before the start if the last interglacial. This section lies above ice that at the time could not be dated reliably other than to show that it may be older than about 750 ka. This stemmed from its lack of the radioactive ^{36}Cl formed, similarly to ^{14}C, by cosmic-ray interactions with stable ^{35}Cl in atmospheric salt aerosols: such cosmogenic chlorine can be used for radiometric dating of ice younger than 750 ka.

A News Feature in the 29 January issue of *Science* (Qiu, J. 2016. Tibet's primeval ice. *Science*, v. **351**, p. 436-439; DOI: 10.1126/science.351.6272.436) focused on the preliminary results of an expedition, led by Yao Tandong of the Institute of Tibetan Plateau Research, Beijing and Lonnie Thompson of Ohio State University, Columbus, to drill a further five ice cores at Guliya in September 2015, one of which penetrated over 300 m of glacial ice. It is now possible to date ice layers back to a million years using argon isotopes. Combined with stable isotope and other measurements through the cores, the dating should provide a huge amount of new information on the evolution of the monsoon, which is currently understood only vaguely. Such information would sharpen models of how the monsoon system works and even hint at how it might change during a period of anthropogenic warming. An estimated 1.4 billion people – a fifth of humanity – who live in the Indian subcontinent, China and SE Asia depend for their food-production on the monsoon.

With less humanitarian urgency but equally fascinating is the discovery that, as well as sea-ice, the central Arctic Ocean once hosted vast ice shelves during the last-but-one glacial episode (Jakobsson, M. and 24 others 2016. Evidence for an ice shelf covering the central Arctic Ocean during the penultimate glaciations. *Nature Communications*, v. **7**, DOI: 10.1038/ncomms10365). Clues emerged from multibeam sonar bathymetry that created detailed images of topography on the floor of the Arctic Ocean. These revealed sets of parallel ridges on the shallowest parts of the polar basin, thought to have formed when moving ice shelves grounded. The depths of the grooved areas indicate ice thicknesses up to and exceeding 1 km. The grooves look very similar to the large-scale lineaments that formed on the surface of the Canadian Shield when the Laurentide ice sheet ground its way from zones of glacial accumulation. Grounding of an ice shelf would have resulted in its thickening in the upflow direction as a result of plastic deformation of the ice, tending to lock the flow and direct ice escape over the deeper parts of the Arctic basin.

An Antarctic Ice Shelf (Credit: Georges Nijs Flickr)

Back-tracking the grooves defines the ice shelf's source regions in the northern Canadian islands, north Scandinavia and the lowlands of eastern Siberia as well as regional flow patterns and the extent of floating continental ice. The last is a major surprise: at over 4 million km^2 it was four times larger than all modern Antarctic ice shelves. The ice moved to 'escape' to the North Atlantic Ocean through the Fram Strait between East Greenland and Svalbard (Spitzbergen). Dating sediment stratigraphy in the grooved areas using magnetic and fossil data shows that the ice shelves existed between 160 and 140 ka during the penultimate glacial maximum. For such a mass of glacial ice to be expelled into the Arctic Ocean implies that a great deal more snow fell on its fringes then than during the last glacial maximum. Another possibility is that the huge mass of floating ice regulated the salinity and density of the upper Atlantic in a different way from the periodic iceberg 'armadas' that characterized the last glacial epoch and help account for a whole number of sudden warming and cooling events.

Related article: Domack, E. 2016. A great Arctic ice shelf. *Nature*, v. **530**, p. 163-164; DOI: 10.1038/nature16878.

Salt and Earth's atmosphere (*July 2016*)

It is widely known that glacial ice contains a record of Earth's changing atmospheric composition in the form of bubbles trapped when the ice formed. That is fine for investigations going back about a million years, in particular those that deal with past climate change. Obviously going back to the composition of air tens or hundreds of million years ago cannot use such a handy, direct source of data, but has relied on a range of indirect proxies. These include the number of pores or stomata on fossil plant leaves for CO_2, variations in sulfur isotopes for oxygen content and so on. Variation over time of the atmosphere's content of oxygen has vexed geoscientists a great deal, partly because it has probably been tied to biological evolution: forming by some kind of oxygenic photosynthesis and being essential for the rise to dominance of eukaryotic animals such as ourselves. Its presence or absence also has had a large bearing on weathering and the associated dissolution or precipitation of a variety of elements, predominantly iron. Despite progressively more clever proxies to indicate the presence of oxygen, and intricate geochemical theory through which its former concentration can be modelled, the lack of an opportunity to calibrate any of the models has been a source of deep frustration and acrimony among researchers.

Yet as is often said, there are more ways of getting rid of cats than drowning them in butter. The search has been on for materials that trap air in much the same way as does ice, and one popular, if elusive target has been the bubbles in crystals of evaporite minerals. The trouble is that most halite deposits formed by precipitation of NaCl from highly concentrated brines in evaporating lakes or restricted marine inlets. As a result the bubbles contain liquids that do a grand job of preserving aqueous geochemistry but leave a lot of doubt as regards the provenance of gases trapped within them. For that to be a sample of air rather than gases once dissolved in trapped liquid, the salt needs to have crystallized above the water surface.

Underground rock salt mining (credit: Salt Institute)

That may be possible if salt forms from brines so dense that crystals are able to float, or perhaps where minerals such as gypsum form as soil moisture is drawn upwards by capillary action to form 'desert roses'. A multinational team, led by Nigel Blamey of Brock University in Canada, has published results from Neoproterozoic halite whose chevron-like crystals suggest subaerial formation (Blamey, N.J.F. and 7 others, 2016. Paradigm shift in determining Neoproterozoic atmospheric oxygen. *Geology*, v. **44**, p. 651-654; DOI: 10.1130/G37937.1). Multiple analyses of five halite samples from an ~815 Ma-old horizon in a drill core from the Neoproterozoic Canning Basin of Western Australia contained about 11% by volume of oxygen, compared with 25% from Cretaceous salt from China, 20% of late-Miocene age from Italy, and 19 to 22% from samples modern salt of the same type.

Although the Neoproterozoic result is only about half that present in modern air, it contradicts results that stem from proxy approaches, which suggest a significant rise in atmospheric oxygenation from 2 to about 18% during the younger Cryogenian and Ediacaran Periods of the Neoproterozoic, when marine animal life made explosive developments at the time of repeated Snowball Earth events. Whether or not this approach can be extended back to the Great Oxygenation Event at around 2.3 Ga ago and before depends on finding evaporite minerals that fit stringent criteria for having formed at the surface: older deposits are known even from the Archaean.

Global warming: Bury the beast in basalt (*June 2016*)

Global warming cannot simply be reversed by turning off the burning of fossil fuels. Two centuries' worth of accumulated anthropogenic carbon dioxide would continue to trap solar energy, even supposing that an immediate shutdown of emissions was feasible: a fantasy for any kind of society hooked on coal, oil and gas. It takes too long for natural processes to download CO_2 from the atmosphere into oceans, living organic matter or, ultimately, back once more into geological storage. In the carbon cycle, it has been estimated that an individual molecule of the gas returns to one of these 'sinks' in about 30 to 95 years. But that is going on all the time for both natural and anthropogenic emissions. Despite the fact that annual human emissions are at present only about 4.5 % of the amount emitted by natural processes, the drawdown processes in the carbon cycle are clearly incapable of balancing them at present. Currently the anthropogenic excess of CO_2 over that in the pre-industrial atmosphere is more than 100 parts per million achieved in only 250 years or so.

The record of natural CO_2 levels measured in cores through polar ice caps suggests that natural processes would take between 5 to 20 thousand years to achieve a reduction of that amount.
Whatever happens as regards international pledges to reduce emissions, such as those reported by the Paris Agreement, so called 'net-zero emissions' leave the planet still a lot warmer than it would be in the 'natural course of things'. This is why actively removing atmospheric carbon dioxide seems to be the most important thing on any realistic agenda. The means of carbon sequestration that is most widely touted is pumping emissions from fossil fuel burning into deep geological storage (carbon capture and storage or CCS), but oddly that did not figure in the Paris Agreement (see *Paris Agreement 2015: carbon capture and storage* December 2015). In that post I noted that CCS promised by the actual emitters was not making much progress: a cost of US$50 to 100 per tonne sequestered would make most fossil fuel power stations unprofitable. Last week CCS hit the worlds headlines through reports that an Icelandic initiative to explore a permanent, leak-proof approach had made what appears to be a major breakthrough (Matter, J.M. and 17 others, 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, v. **352**, p. 1312-1314; DOI: 10.1126/science.aad8132). In January 2009 I discussed the method that has now been tested in Iceland (*Mantle rock and carbon dioxide sequestration*). It stems from the common observation that some of the minerals in mafic and ultramafic igneous rocks tend to breakdown in the presence of carbon dioxide dissolved in slightly acid water. The minerals are olivine ($[Fe,Mg]_2SiO_4$)] and pyroxene ($[Fe,Mg]CaSi_2O_6$), from whose breakdown the elements calcium and magnesium combine with CO_2 to form carbonates.

Iceland is not short of basalts, being on the active, axial ridge of the North Atlantic. Surprisingly for a country that uses geothermal power to generate electricity it is not short of carbon dioxide emissions either, as the hot steam contains large quantities of it. In 2012 the CarbFix experiment began to inject a 2 km deep basalt flow with 220 t of geothermal CO_2 'spiked' with ^{14}C to check where the gas had ended up. This experiment was in two phases, each about 3 months long. After 18 months the pump that extracted groundwater directly from the lava flow for continuous monitoring of changes in the tracer and pH broke down. The fault was due to a build up of carbonate – a cause for astonishment and rapid evaluation of the data gathered. In just 18 months 95% of the ^{14}C in the injected CO_2 had been taken up by carbonation reactions. A similar injection experiment into the Snake River flood basalts in Washington State, USA, is said to have achieved similar results (not yet published). A test would be to drill core from the target flow to see if any carbonates containing the radioactive tracer filled either vesicles of cracks in the rock – some press reports have shown Icelandic basalt cores that contain carbonates, but no evidence that they contain the tracer.

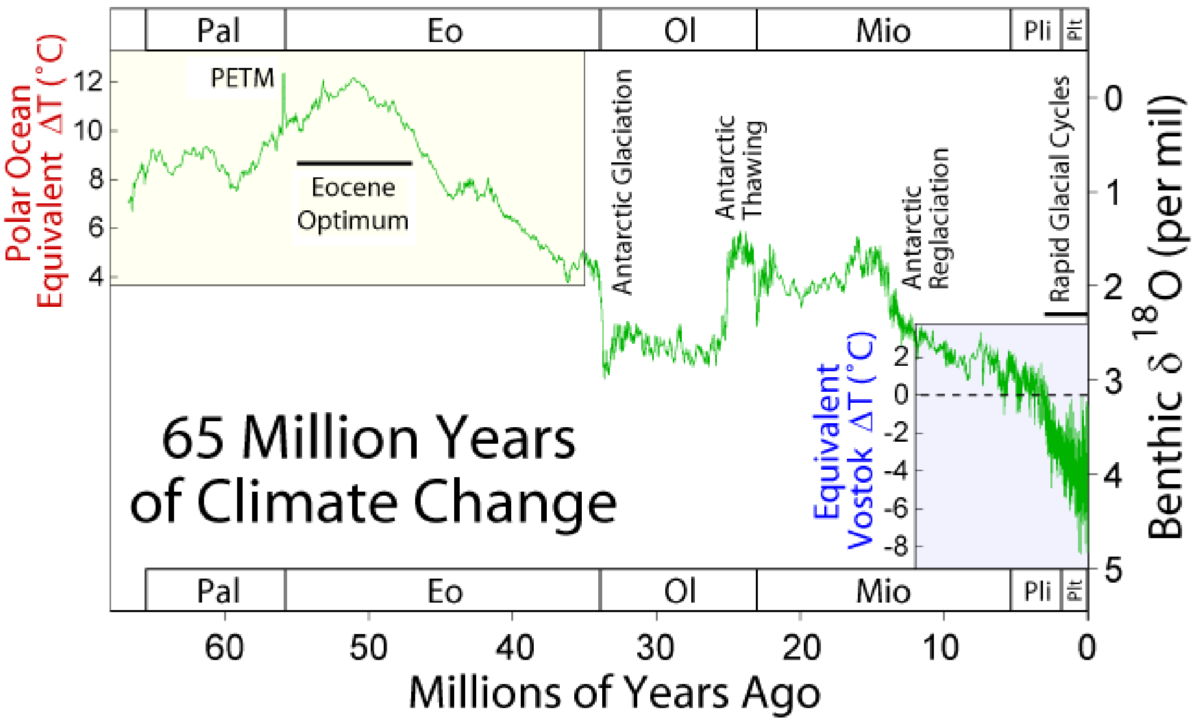
Although this seems a much more beneficial use of well-injection than fracking, the problem is essentially the same as reinjection of carbon dioxide into old oil and gas fields; the high cost. Alternatives might be to spread basaltic or ultramafic gravel over large areas so that it reacts with CO_2 dissolved in rainwater or to lay bear fresh rocks of that kind by removal of soil cover.

Related articles:

Kintisch, E., 2016. Underground injections turn carbon dioxide to stone. *Science*, v. **352**, p. 1262-1263. In a first, Iceland power plant turns carbon emissions to stone. (*Phys.org*)

Impact linked to the Palaeocene-Eocene boundary event (*October 2016*)

The Palaeocene–Eocene (P-E) boundary at 55.8 Ma marks the most dramatic biological changes since the mass extinction at the Cretaceous-Palaeogene boundary 10 million years earlier. They included the rapid expansions of mammals and land plants and major extinction of deep-water foraminifera. It was a time of sudden global warming (5-10°C in 10-20 ka) superimposed on the general Cenozoic cooling from the 'hothouse' of the Cretaceous Period. It coincided with a decrease in the proportion of ^{13}C in marine carbonates. Because photosynthesis, the source of organic carbon, favours light ^{12}C, such a negative $\delta^{13}C$ "spike" is generally ascribed to an unusually high release of organic carbon to the atmosphere. The end-Palaeocene warming may have resulted from a massive release of methane from gas-hydrate buried in shallow seafloor sediments. But another process may yield such a signature; massive burning of organic material at the land surface. Since its discovery, the P-E thermal maximum has been likened to the situation that we may face should CO_2 emissions from fossil-fuel burning continue to rise without control. Unsurprisingly, funds are more easily available for research on this topic than, say, 'Snowball Earth' events.



Climate change during the last 65 million years. The Paleocene–Eocene Thermal Maximum is labelled PETM. (Credit: Robert A. Rohde)

Three seafloor sediment cores off the east coast of the US that include the P-E boundary have been found to contain evidence for an impact that occurred at the time of the $\delta^{13}C$ "spike" (Schaller, M.F. *et al*. 2016. Impact ejecta at the Paleocene-Eocene boundary. *Science*, v. **354**, p. 225-229; DOI: 10.1126/science.aaf5466). The evidence is dominated by tiny spherules and tear-shaped blobs of glass, some of which contain tiny crystals of shocked and high-temperature forms of silica (SiO_2). These form part of the suite of features that have been used to prove the influence of asteroid impacts. Two other onshore sites have yielded iridium anomalies at the boundary, so it does look like there was an impact at the time. The question is, was it large enough either to cause vast amounts of methane to blurt out from shall-water gas hydrates or set the biosphere in fire? Two craters whose age approximates that of the P-E boundary are known, one in Texas the other in Jordan, with diameters of 12 and 5 km respectively; far too small to have had any global effect. So either a suitably substantial crater of the right age is hidden somewhere by younger sediments or the association is coincidental – the impact that created the Texan crater could conceivably have flung glassy ejecta to the area of the three seafloor drilling sites.

Almost coinciding with the spherule-based paper's publication another stole its potential thunder. Researchers at Southampton University used a mathematical model to investigate how a methane release event might have unfolded (Minshull, T.A. *et al*. 2016. Mechanistic insights into a hydrate contribution to the Paleocene-Eocene carbon cycle perturbation from coupled thermohydraulic simulations. *Geophysical Research Letters*, v. **43**, p. 8637-8644, DOI: 10.1002/2016GL069676). Their findings challenge the hypothesized role of methane hydrates in causing the sudden warming at the P-E boundary. But that leaves out the biosphere burning, which probably would have needed a truly spectacular impact.

More on mechanisms for ancient climate change