Climate change and palaeoclimatology

Climate change and global volcanism (*March 2013*)

Geologists realized long ago that volcanic activity can have a profound effect on local and global climate. For instance, individual large explosive eruptions can punch large amounts of ash and sulfate aerosols into the stratosphere where they act to reflect solar radiation back to space, thereby cooling the planet. The 1991 eruption of Mt Pinatubo in the Philippines ejected 17 million tonnes of SO_2; so much that the amount of sunlight reaching the Northern Hemisphere fell by around 10% and mean global temperature fell by almost 0.5 °C over the next 2 years. On the other hand, increased volcanic emissions of CO_2 over geologically long periods of time are thought to explain some episodes of greenhouse conditions in the geological past.

Ash plume of Mount Pinatubo during its 1991 eruption. (credit: Wikipedia)

The converse effect of climate change on volcanism has, however, only been hinted at. One means of investigating a possible link is through the records of volcanic ash in sea-floor sediment cores in relation to cyclical climate change during the last million years. Data relating to the varying frequency volcanic activity in the circum Pacific 'Ring of Fire' has been analysed by German and US geoscientists (Kutterolf, S. *et al*. 2013. A detection of Milankovich frequencies in global volcanic activity. *Geology*, v. **41**, p. 227-230; doi:10.1130/G33419.1) to reveal a link with the 41 ka periodicity of astronomical climate forcing due to changes in the tilt of the Earth's axis of rotation. This matches well with the frequency spectrum displayed by changes in oxygen isotopes from marine cores that record the waxing and waning of continental ice sheets and consequent falls and rises in sea level. Yet there is no sign of links to the orbital eccentricity (~400 and ~100 ka) and axial precession (~22 ka) components of Milankovitch climatic forcing. An interesting detail is that the peak of volcanism lags that of tilt-modulated insolation by about 4 ka.

At first sight an odd coincidence, but both glaciation and changing sea levels involve shifting the way in which the lithosphere is loaded from above. With magnitudes of the orders of kilometres and hundreds of metres respectively glacial and eustatic changes would certainly affect the gravitational field. In turn, changes in the field and the load would result in stress changes below the surface that conceivably might encourage subvolcanic chambers to expel or accumulate magma. Kutterolf and colleagues model the stress from combined glacial and marine loading and unloading for a variety of volcanic provinces in the 'Ring of Fire' and are able to show nicely how the frequency of actual eruptions fits changing rates of deep-crustal stress from their model. Eruptions bunch together when stress changes rapidly, as in the onset of the last glacial maximum and deglaciations, and also during stadial-interstadial phases.

Whether or not there may be a link between climate change and plate tectonics, and therefore seismicity, is probably unlikely to be resolved simply because records do not exist for earthquakes before the historic period. As far as I can tell, establishing a link is possible only for volcanism close to coast lines, i.e. in island arcs and continental margins, and related to subduction processes, because the relative changes in stress during rapid marine transgressions and recessions would be large.. Deep within continents there may have been effects on volcanism related to local and regional ice-sheet loading. In the ocean basins, however, there remains a possibility of influences on the activity of ocean-island volcanoes, though whether or not that can be detected is unclear. Some, like Kilauea in Hawaii and La Palma in the Canary Islands, are prone to flank collapse and consequent tsunamis that could be influenced by much the same process. Another candidate for a climate-linked, potentially catastrophic process is that of destabilisation of marine sediments on the continental edge, as in the Storegga Slide off Norway whose last collapse and associated tsunami around 8 thousand years ago took place during the last major rise in sea level during deglaciation. The climatic stability of the Holocene probably damps down any rise in geo-risk with a link to rapid climate change, which anthropogenic changes are likely to be on a scale dwarfed by those during ice ages.

Arctic climate in the run-up to the Great Ice Age (*June 2013*)

Around 3.6 Ma ago a large extraterrestrial projectile slammed into the far north-east of Siberia forming crater 16 km across. The depression soon filled with water to form Lake El'gygytgyn, on whose bed sediments have accumulated up to the present. A major impact close to the supposed start of Northern Hemisphere glacial conditions was a tempting target for coring: possibly two birds with one stone as the lowest sediments would probably be impact debris and boreal lake sediments of this age are as rare as hens' teeth. The sedimentary record of Lake El'gygytgyn has proved to be a climate-change treasure trove (Brigham-Grette, J and 15 others 2013. Pliocene warmth, polar amplification, and stepped Pleistocene cooling recorded in NE Arctic Russia. *Science*, v. **340**, p. 1421-1426; DOI: 10.1126/science.1233137).

Lake El’gygytgyn impact crater. (credit: Wikipedia)

The team of US, Russian, German and Swedish scientists discovered that the sedimentary record was complete over a depth of 318 m and so promised a high resolution climate record. The striking feature of the sediments is that they show cyclical variation between five different facies, four of which are laminated and so preserve intricate records of varying weathering and sediment delivery to the lake. The sediments also contain pollens and diatom fossils, and yield good magnetic polarity data. The last show up periods of reversed geomagnetic polarity, which provide age calibration independent of relative correlation with marine isotope records.

A host of climate-related proxies, including pollen from diverse tree and shrub genera, variations in silica due to changes in diatom populations and organic carbon content in the cyclically changing sedimentary facies are correlated with global climate records based on marine-sediment stable isotope. These records reveal intricate oscillations between cool mixed forest, cool coniferous forest, taiga and cold deciduous forest, with occasional frigid tundra conditions through the mid- to late Pliocene. Compared with modern conditions NE Siberia was much warmer and wetter at the start of the record. Around the start of the Pleistocene sudden declines to cooler and drier conditions appear, although until 2.2 Ma ago average summer conditions seem to have been higher that at present, despite evidence from marine proxies of the onset of glacial-interglacial cycles in the Northern Hemisphere.

In detail, Lake El’gygytgyn revealed some surprises including rapid onset of a lengthy cold-dry spell of tundra conditions between 3.31 to 3.28 Ma. The first signs that the lake was perennially frozen appear around 2.6 Ma, well before evidence for the first continental glaciation in North America, presaged by signs around 2.7 Ma that winters consistently became colder than present ones. Overall the lake record presents a picture of a stepped shift in climate in the run-up to the Great Ice Age. Lake El’gygytgyn seems set to become the standard against which other, more patchy records around the Arctic Ocean are matched and correlated. Indeed it is the longest and most detailed record of climate for the Earth's land surface, compared with 120 and 800 ka for the Greenland and Antarctic ice-caps.

Modelling their findings against likely atmospheric CO_2 levels the authors provide grist to the media mill which focuses on how the late Pliocene may be a model for a future warm Earth if emissions are not curtailed, with visions of dense polar forests

Related articles: Arctic Tundra 'Will Turn to Forest' (truthdig.com)

Yes, it was hot during the Permian (*June 2013*)

For those of us living in what was the heart of Pangaea – Europe and North America – more than 250 Ma ago this item's title might seem like the ultimate truism. However, despite our vision of desert dune sands and evaporating inland seas, glaciation blanketed much of the Gondwana part of the supercontinent until the Middle Permian then lying athwart the South Pole. That would go a long way to accounting for extreme dryness at low to mid-latitudes, especially in the deep interior of Pangaea, but just how hot might tropical climates have been? The deglaciation of Gondwana was abrupt and has been touted as an analogue for a possible anthropogenic closure to the Cenozoic glacial epoch that began around 34 Ma in Antarctica and has periodically gripped land at northern latitudes as low as 40°N for the last 2.5 Ma. Since the present distribution of continents is totally different from the unique pole-to-pole shape of Pangaea, that is probably a view that is not widely held by palaeoclimatologists. Nonetheless, getting hard data on Permian conditions has an intrinsic interest for most geoscientists.

Playa lake in Death Valley, USA (credit: Wikipedia)

One of the best ways of measuring past temperatures, whether surficial or deep within the crust, almost directly is based on fluids trapped within minerals formed at the time of interest. In Permian strata there is no shortage of suitable material in the form of evaporite minerals, especially common salt or halite. A distinctive chevron-like texture develops in halite that forms at the water-atmosphere interface in playa lakes that dry out every year. When thin sections of samples that contain fluid inclusions are slowly heated the air bubbles trapped in salt during crystallisation gradually homogenise with the other trapped fluids. Based on samples that have formed at the present day under a range of air temperatures, the temperature of homogenisation indicates the prevailing air temperature accurately. So well, in fact, that it is possible to assess diurnal temperature variations in suitable halite crystals.

Results have been obtained from Middle Permian halites in Kansas, USA (Zambito, J.J. & Benison, K.C. 2013. Extremely high temperatures and paleoclimate trends recorded in Permian ephemeral lake halite. *Geology*, v. **41**, p. 587-590; DOI: 10.1130/G34078.1). In part of the section studied air temperatures reached 73°C, compared with a modern maximum of 57°C recorded in halites from the playas of Death Valley. Moreover, they exhibit changes of more than 30°C during daily cycles. But that kind of weather is common in other hot dry areas today, such as the Dasht-e Lut in eastern Iran. Also, the full data show crystallisation at lower temperatures (maxima of 30-40°C) in part of the sequence. What is noteworthy is that these data are the first quantitative indicators of weather before the last 2.5 Ma. Since evaporites extend back into the Precambrian, the method will undoubtedly extend accuracy and precision to paleoclimate where only proxies and a modicum of guesswork were previously available.

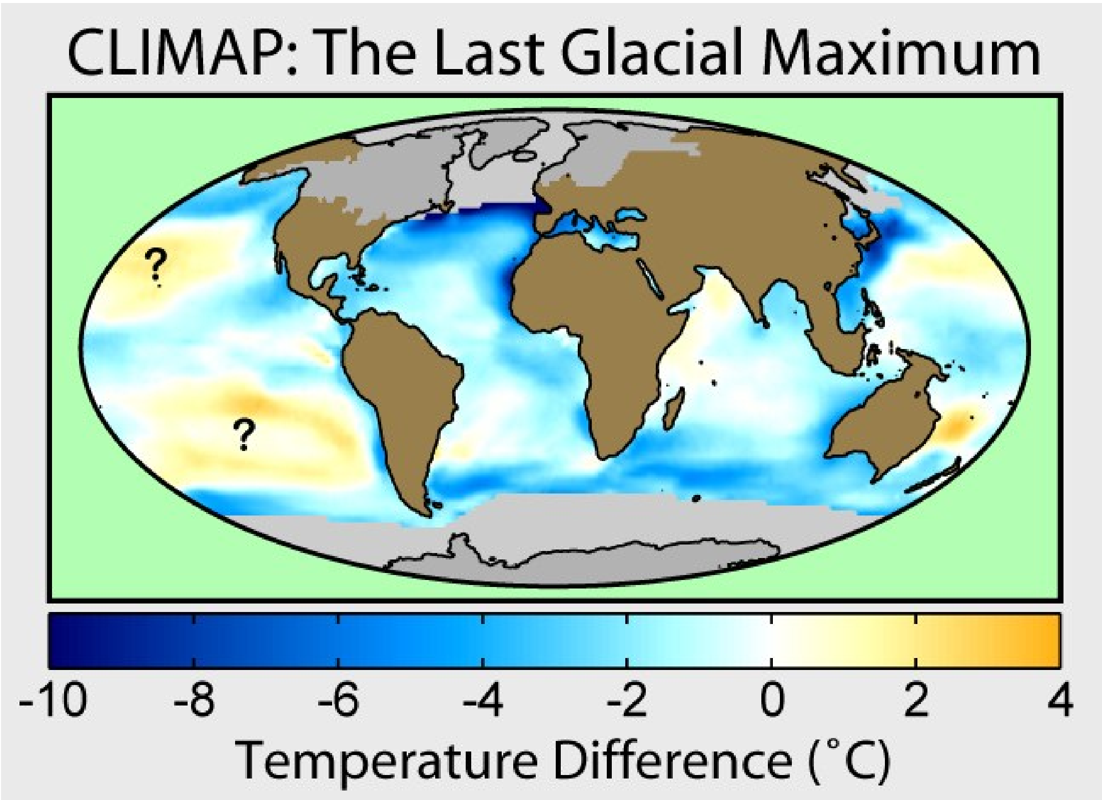
New approach to the Milankovitch mystery (*August 2013*)

Melting pond on the Greenland ice sheet (credit: Photo by Leif Taurer)

Milutin Milankovitch's astronomical theory to account for glacial – interglacial cycles is based on 3 gravitational influences on the Earth that change the way it spins and orbits the Sun. Each is cyclic but with different periods: the angle of axial tilt every 41 ka; precession of its rotation axis on a 23 ka pacing; the change in shape of the orbit around the Sun over 100 ka. Each subtly affects the amount of solar energy, their influences combining to produce a seemingly complex, but predictable variation through time of solar heating for any point on the Earth's surface. Milankovitch's work was triumphantly confirmed when analysis of oxygen-isotope time series from sea-floor sediments revealed precisely these periods in the record of continental ice cover. Specifically, astronomical pacing of midsummer insolation at 65°N matches the real climatic pattern through time.

Yet the periods between glacial maxima have not stayed constant over the last 2 Ma or so (Figure showing Phanerozoic climate changes). About 0.8 to 1 Ma ago a sequence with roughly 41 ka spacing was replaced by another about every 100 ka, i.e. both overall climate periods matched one of the astronomical forcings. What is a puzzle is that the current periodicity seems to follow the very weakest influence in energy terms; that from orbital eccentricity. The energy shifts from changes in orbit shape are, in fact, far too weak to drive the accumulation and eventual melting of ice sheets on land. Climatologists have suggested a variety of processes that might be paced by eccentricity but which act to amplify is climatic 'signal'. None have been especially convincing.

In an attempt to resolve the mystery Ayako Abe-Ouchi of the University of Tokyo and Japanese, US and Swiss colleagues linked a climate model driven by Milankovitch insolation and variations in CO_2 recorded in an Antarctic ice core with a model of how land-ice forms and interacts with the underlying lithosphere (Abe-Ouchi, A. *et al*. 2013. Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature*, v. **500**, p. 190-193; doi: 10.1038/nature12374).



Map of ice sheets, sea temperature changes, and changes in the outline of coastal regions during the last glacial maximum. (credit: Wikipedia)

Their key discovery is that the ice-sheets that repeatedly formed on the Canadian Shield and extended further south than Chicago had such a huge mass that they changed the shape of the land surface beneath them so much it had an effect on climate as a whole. The reason for this is that glacial loading forces the lithosphere down by displacing the more ductile asthenosphere sideways. But when melting begins rebound of the rock surface lags a long time behind the shrinking ice volume – well displayed today in Britain and Scandinavia by continued rise of the land to form raised beaches. In the case of the North American ice sheet, what had become an enormous ice bulge at glacial maxima developed into a huge basin up to 1 km deep as the ice began to melt. Simply by virtue of its low elevation this sub-continental basin would have warmed up more and more rapidly as the ice-surface fell because of this 'isostatic' lag.

Another feature to emerge from the model was the interaction between the 100 ka eccentricity 'signal' and that of precession at 23 ka. For long periods that kept summer temperature low enough for snow to pile up and become glacial ice, but on a roughly 100 ka time scale both acted together to increase summer temperatures at high northern latitudes. Melting that instantaneously removed some ice load each summer brought into play the sluggish isostatic response that helped even more warming the following year. As well as convincingly accounting for the 100 ka mystery, the model explains the far more rapid deglaciations in that mode than in the preceding 41 ka cycles, which were almost symmetrical compared with the more recent slow accumulation of continental ice sheets over ~90 ka followed by almost complete melting in a mere 10 ka.

If true, the model seems to imply that before 800 ka the positions, thicknesses and extents of continental ice sheets were different from those in later times. Or perhaps it reflects a steady increase in the overall volume of ice being produced over northern North America, or that glacial erosion thinned the crust until changing isostatic influences could 'trip' sufficient additional warming.

Related articles: Kerr, R.A. 2013. How to make a Great Ice Age, Again and again and again. *Science*, v. **341**, p. 599; DOI: 10.1126/science.341.6146.599; The Milankovitch Cycles (muchadoaboutclimate.wordpress.com); Useful link for climate science (muchadoaboutclimate.wordpress.com)

Earth's first major glacial epochs (*November 2013*)

The global glaciations of the Neoproterozoic that reached low latitudes – the so-called 'Snowball Earth' events have dominated accounts of ancient glaciations since the start of the 21st century. Yet they are not the oldest examples of large-scale effects of continental ice sheets. Distinctive tillites or diamictites that contain large clasts of diverse, exotic rocks occur in sedimentary sequences of Archaean and Palaeoproterozoic age. The oldest are dated at around 2.9 Ma in the Pongola Supergroup of Swaziland, South Africa and formed at an estimated palaeolatitude of 48°; within the range of the equatorward extent of Pleistocene ice sheets. No evidence has turned up for glaciation of that age in other regions, and therefore for a 'Snowball Earth' at that time. The surprise is not the antiquity of the Pongola glaciation but the fact that tillites formed by glaciers are not more common in the early part of geological history. The sun has increased in its warming effect since the Earth formed so that the very absence of glaciations over huge spans of early Precambrian time points strongly towards an early atmosphere far richer in greenhouse gases than it is now.

Evidence for Palaeoproterozoic glaciation is more widespread, important tillites occurring in the Great Lakes region of North America and in the Transvaal and Griqualand regions of South Africa. Those of South Africa formed at a latitude of around 10°, suggesting 'Snowball' conditions, and in each region there are multiple tillites in the stratigraphic column. Accurate dating of volcanic ash horizons in the sequences of both areas (Rasmussen, B. *et al*. 2013. Correlation of Paleoproterozoic glaciations based on U-Pb zircon ages for tuff beds in the Transvaal and Huronian Supergroups. *Earth and Planetary Science Letters*, v. **382**, p. 173-

180; DOI: 10.1016/j.epsl.2013.08.037) has made it possible to correlate three glacial deposits precisely between the two now widely separated areas. The dating also reveals that four glacial events occurred over a period of 200 Ma between 2.45 and 2.22 billion years ago: longer than the duration of the Mesozoic Era of the Phanerozoic and about the same as the time span during which 3 or 4 'Snowball' events plastered the planet with ice in the Cryogenian and Ediacaran Periods of the Neoproterozoic.

Diamictite from the Palaeoproterozoic Gowganda Formation in Ontario Canada (credit: Canadian Sedimentology Research Group)

This episode of the first large-scale glaciations neatly brackets the first appearance of significant amounts of oxygen in the Earth's atmosphere during the Great Oxidation Event from 2.45 to 2.2 Ga. It is hard to avoid the conclusion that the two were connected as an increase in oxygen in the air must have influenced the concentration of greenhouse gases, especially that of methane, the most powerful of several that delay loss of heat to space by radiation from the surface. Once oxygen production by photosynthetic organisms exceeded a threshold atmospheric methane would very rapidly have been oxidized away to CO_2 plus water vapour, leaving excess oxygen in the air to prevent the build-up of methane thereafter as is the case nowadays. But what pushed atmospheric composition beyond that threshold? A key piece of evidence lies in the record of different carbon isotopes in seawater of those times, which emerges from their study in Precambrian limestones.

After the end of the Archaean Eon at 2.5 Ga the proportion of marine ^{13}C to ^{12}C increased dramatically. Its accepted measure ($\delta^{13}C$) changed rapidly from the near-zero values that had previously characterised the Archaean to more than 10; an inflated value that lingered for much of the half-billion years that spanned the Great Oxidation Event and the Palaeoproterozoic glaciations (Martin, A.P. *et al*. 2013. A review of temporal constraints for the Palaeoproterozoic large, positive carbonate carbon isotope excursion (the Lomagundi–Jatuli Event). *Earth-Science Reviews*, v. **127**, p. 242-261; DOI: 10.1130/G23764A.1). Later times saw δ^{13}C return to hovering between slightly negative and slightly positive values either side of zero until the Neoproterozoic when once more 'spikes' affected the C-isotope record during the period of the better known 'Snowball' events. What lay behind this very broad carbon-isotope anomaly?

To increase ^{13}C at the expense of ^{12}C requires to removal from seawater of very large amounts of the lighter isotope. The only likely mechanism is the prolonged and permanent burial of masses of organic material, the only substances that selectively take up ^{12}C. In turn, that implies a huge increase in biological productivity and its efficient burial without being oxidised to CO_2 plus water. There are three possibilities: oxygen was absent from the ocean floor; sedimentation was too fast for oxidising bacteria to keep pace or such bacteria did not evolve until the end of the Lomagundi–Jatuli Event. It seems likely that such a dramatic change in the biosphere may have marked some fundamental shift in biological evolution not long after the close of the Archaean. Whichever, the biosphere somehow increased its capacity to generate oxygen. Since oxygen is anathema to many kinds of anaerobic bacteria and archaea, probably the only kinds of organism at the outset of these events, it is possible to imagine continual extinctions yet to maintain high biological productivity new organisms may have emerged to replace those that vanished. By 2.0 Ma, the first putative eukaryote cells (those with nuclei and a variety of organelles) had appeared.