# *Climate change and palaeoclimatology*

**Ancient CO2 estimates worry climatologists (*January 2017*)**

Concerns about impending, indeed actual, anthropogenic climate change brought on by rapidly rising levels of the greenhouse gas carbon dioxide have spurred efforts to quantify climates of the distant past. Beyond the $CO_2$ record of the last 800 ka established from air bubbles trapped in glacial ice palaeoclimate researchers have had to depend on a range of proxies for the greenhouse effect. Those based on models linking plate tectonic and volcanic $CO_2$ emissions with geological records of the burial of organic matter, weathering and limestone accumulation are imprecise in the extreme, although they hint at considerable variation during the Phanerozoic. Other proxies give a better idea of the past abundance of the main greenhouse gas, one using the curious openings or stomata in leaves that allow gases to pass to and fro between plant cells and the atmosphere. Well preserved fossil leaves show stomata nicely back to about 400 Ma ago when plants first colonised the land.

Stomata on a rice leaf (Credit: Getty images)

Stomata draw in $CO_2$ so that it can be combined with water during photosynthesis to form carbohydrate. So the number of stomata per unit area of a leaf surface is expected to increase with lowering of atmospheric $CO_2$ and vice versa. This has been observed in plants grown in different air compositions. By comparing stomatal density in fossilised leaves of modern plants back to 800 ka allows the change to be calibrated against the ice-core record. Extending this method through the Cenozoic, the Mesozoic and into the Upper Palaeozoic faces the problems of using fossils of long-extinct plant leaves. This is compounded by plants' exhalation of gases to the atmosphere – some $CO_2$ together with other products of photosynthesis, oxygen and water vapour. Increasing stomatal density when carbon dioxide is at low concentration risks dehydration. How extinct plant groups coped with this problem is, unsurprisingly, unknown. So past estimates of the composition of the air become increasingly reliant on informed guesswork rather than proper calibration. The outcome is that results from the distant past tend to show very large ranges of $CO_2$ values at any particular time.

An improvement was suggested some years back by Peter Franks of the University of Sydney with Australian, US and British co-workers (Franks, P.J. *et al*. 2014. New constraints on atmospheric $CO_2$ concentration for the Phanerozoic. *Geophysical Research Letters*, v. **41**, p. 4685-4694; DOI: 10.1002/2014GL060457). Their method included a means of assessing the back and forth exchange of leaf gases with the atmosphere from measurements of the carbon isotopes in preserved organic carbon in the fossil leaves, and combined this with stomatal density and the actual shape of stomata. Not only did this narrow the range of variation in atmospheric $CO_2$ results for times past, but the mean values were dramatically lessened. Rather than values ranging up to 2000 to 3000 parts per million (~ 10 times the pre-industrial value) in the Devonian and the late-Triassic and early-Jurassic, the gas-exchange method does not rise above 1000 ppm in the Phanerozoic.

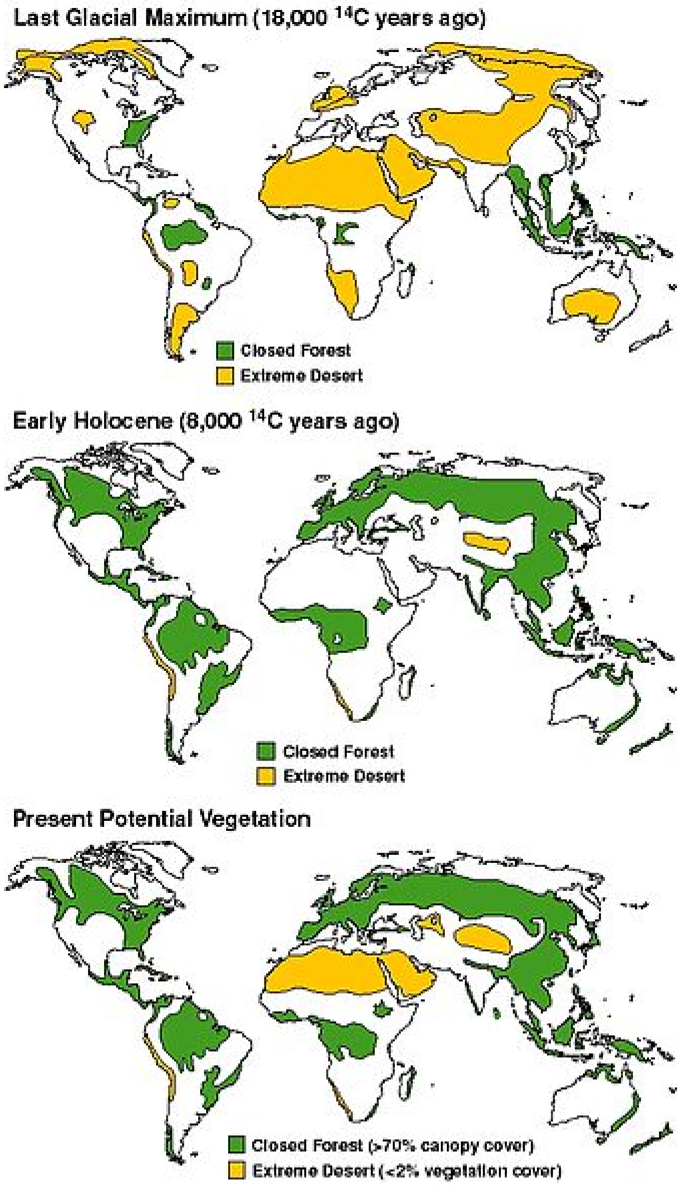
The upshot of these findings strongly suggests that the Earth's climate sensitivity to atmospheric $CO_2$ (the amount of global climatic warming for a doubling of pre-industrial $CO_2$ concentration) may be greater than previously thought; around 4° rather than the currently accepted 3°C. If this proves to be correct it forebodes a much higher global temperature than present estimates by the Intergovernmental Panel on Climate Change (IPCC) for various emission scenarios through the 21$^{st}$ century.

**See also:** Hand, E. 2017. Fossil leaves bear witness to ancient carbon dioxide levels. *Science*, v. **355**, p. 14-15; DOI: 10.1126/science.355.6320.14. Heather Kelly 2017. How did plants evolve stomata. (heatherkellyblog.wordpress.com)

### Amazonian forest through the last glacial maximum (*January 2017*)

Accelerated evolution may occur when a small population of a species – whose genetic variability is therefore limited – becomes isolated from all other members. This is one explanation for the rise of new species, as in the Galapagos archipelago. Creation of such genetic bottlenecks encourages rapid genetic drift away from the main population. It has been suggested to explain sudden behavioural shifts in anatomically modern humans over the last hundred thousand years or so, partly through rapid and long-distance migrations and partly through a variety of environmental catastrophes, such as the huge Toba eruption around 74 ka. Another example has been proposed for the teemingly diverse flora and fauna of the Amazon Basin, particularly among its ~7500 species of butterflies, which has been ascribed to shrinkage of the Amazonian rain forest to isolated patches that became refuges from dry conditions during the last glacial maximum.

A great deal of evidence suggests that during glacial maxima global climate became considerably drier than that in interglacials, low-latitude deserts and savannah grasslands expanding at the expense of humid forest. Yet the emerging complexity of how climate change proceeds from place to place suggests that evidence such continental drying from one well-documented region, such as tropical Africa, cannot be applied to another without confirming data. Amazonia has been the subject of long-standing controversy about such ecological changes and formation of isolated forest 'islands' in the absence of definitive palaeoclimate data from the region itself. A multinational team has now published data on climatic humidity changes over the last 45 ka in what is now an area of dense forest but also receives lower rainfall than most of Amazonia; i.e. where rolling back forest to savannah would have been most likely to occur during the last glacial maximum (Wang, X. *et al*. 2017. Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature*, v. **541**, p. 204-207; DOI: 10.1038/nature20787).




Potential forest cover inferred from global climate models for the last glacial maximum (top) the Holocene thermal maximum and at present. (Credit: Wikipedia)

Their study area is tropical karst, stalagmites from one of whose caves have yielded detailed oxygen-isotope time series. Using the U/Th dating technique has given the data a time resolution of decades covering the global climatic decline into the last glacial maximum and its recovery to modern times. The relative abundance of oxygen isotopes (expressed by $\delta^{18}O$) in the calcium carbonate layers that make up the stalagmites is proportional to that of the rainwater that carried calcium and carbonate ions dissolved from the limestones. The rainwater $\delta^{18}O$ itself depended on the balance between rainfall and evaporation, higher values indicating reduced precipitation. Relative proportions of carbon isotopes in the stalagmites, expressed by $\delta^{13}C$, record the balance of trees and grasses, which have different carbon-isotope signatures. Rainfall in the area did indeed fall during the run-up to the last glacial maximum, to about 60% of that at present, then to rise to ~142% in the mid-Holocene (6 ka). Yet $\delta^{13}C$ in the stalagmites remained throughout comparable with those in the Holocene layers, its low values being incompatible with any marked expansion of grasses.

Amazonian rain forest north of Manaus, Brazil. (Credit: Rainforest Rescue)

One important factor in converting rain forest to grass-dominated savannah is fire induced by climatic drying. Tree mortality and loss of cover accelerates drying out of the forest floor in a vicious circle towards grassland, expressed today by human influences in much of Amazonia. Fires in Amazonia must therefore have been rare during the last ice age; indeed sediment cores from the Amazon delta do not reveal any significant charcoal 'spike'.

**See also:** Bush, M.B 2017. The resilience of Amazonian forests. *Nature*, v. **541**, p. 167-168; DOI: 10.1038/541167a

### Odds and ends about Milankovich and climate change (*February 2017*)

It is some 40 years since the last explosive development in understanding the way the world works. In 1976 verification of Milutin Milanković's astronomical theory to explain cyclical climate change as expressed by surface processes has had a similar impact as the underpinning of internal processes by the emergence of plate tectonics in the preceding decade. Signals that match the regularity of changes in the Earth's orbital eccentricity and the tilt and precession of its axis of rotation, with periods of roughly 96 and 413 ka, 41 ka, 21 and 26 ka respectively, were found in climate change proxies in deep-sea sediment cores (oxygen isotope sequences from benthonic foraminifera) spanning the last 2.6 Ma. The findings seemed as close to proof as one might wish, albeit with anomalies. The most notable of these was that although Milanković's prediction of a dominant 41 ka effect of changing axial tilt, the strongest astronomical forcing, had characterised cooling and warming cycles in the early Pleistocene, since about a million years ago a ~100 ka periodicity took over – that of the weakest forcing from changing orbital obliquity. Analysis of sedimentary cycles from different episodes in earlier geological history, as during Carboniferous to Permian global frigidity, seemed to confirm that gravitational fluctuations stemming from the orbits of other planets, Jupiter and Saturn especially, had been a continual background to climate change.

All manner of explanations have been offered to explain why tiny, regular and predictable changes in Earth's astronomical behaviour produce profound changes in the highly energetic and chaotic climate system. Much attention has centred on the mathematically based concept of stochastic resonance. That is a phenomenon where weak signals may be induced to show themselves if they are mixed with a random signal – 'white noise' spanning a great range of frequencies. The two resonate at the hidden frequencies thereby strengthening the weak, non-random signal. Noise is already present in the climate system because of the random and highly complex nature of the components of climate itself and the surface processes that it induces.

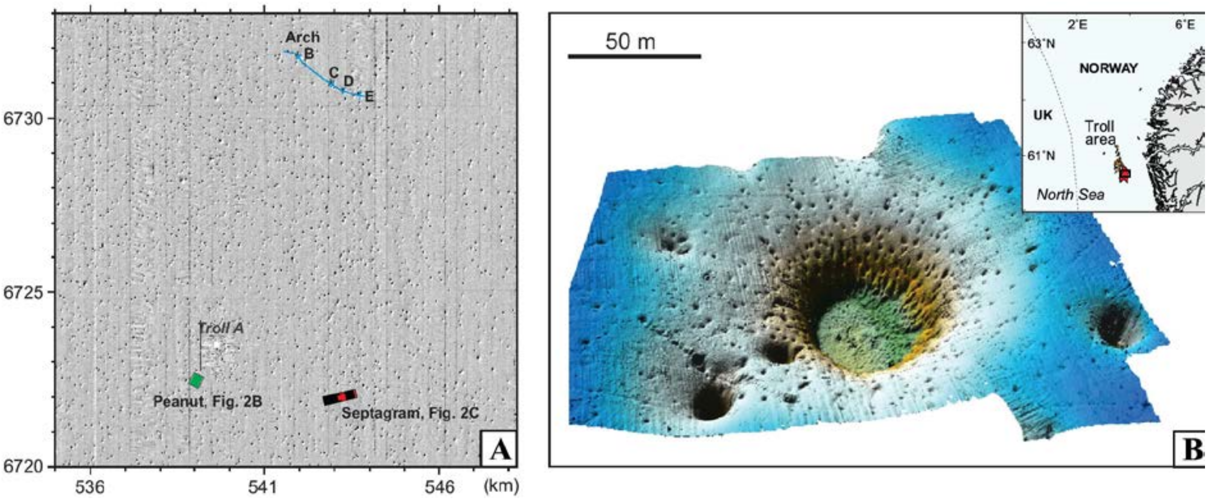
The latest development along these lines suggests that something quite simple may be at the root of inner complexities in the climatic history of the Pleistocene Epoch: the larger an ice sheet becomes and the longer it lasts the easier it is to cause it to melt away (Tzedakis, P.C. *et al*. 2017. A simple rule to determine which insolation cycles lead to interglacials. *Nature*, v. **542**, p. 427-432; DOI: 10.1038/nature21364). The gist of the approach taken in the investigation lies in analysing the degree to which the onsets of major ice-cap melting match astronomically predicted peaks in summer insolation north of 65° N. It also subdivides O-isotope signals of periods of sea level rise into full interglacials, interstadials during periods of climate decline and a few cases of extended interglacials. Through time it is clear that there has been an increase in the number of interstadials that interrupt cooling between interglacials. Plotting the time of peaks in predicted summer warming closest to major glacial melting events against their insolation energy is revealing.

Before 1.5 Ma the peak energy of summer insolation in the Northern Hemisphere exceeded a threshold leading to full interglacials rather than interstadials more often than it did during the period following 1 Ma. Although Milanković's 41 ka periodicity remained recognisable throughout, from about 1.5 Ma ago more and more of the energy peaks resulted in only the partial ice melting of interstadial events. The energy threshold for the full deglaciation of interglacials seems to have increased between 1.5 to 1.0 Ma and then settled to a 'steady state'. The balance between glacial growth and melting increasingly 'skipped' 41 ka peaks in insolation so that ice caps grew bigger with time. Deglaciation then required additional forcing. But considering the far larger extent of ice sheets, the tiny additional insolation due to shifts in orbital eccentricity every ~100 ka surprisingly tipped truly savage ice ages into warm interglacials.

Resolving this paradox may lie with three simple, purely terrestrial factors associated with great ice caps: thicker and more extensive ice becomes warmer at its base and more prone to flow; climate above and around large ice caps becomes progressively colder and drier, so reducing their growth rate; the more sea level falls as land ice builds up, the more the vertical structure and flow of ocean water change. The first of these factors leads to periodic destabilisation when ice sheets surge outwards and increase the rate of iceberg calving into the surrounding oceans. Such 'iceberg armadas' characterised the last Ice Age to result in sudden irregularly spaced changes in ocean dynamics and global climate to return to metastable ice coverage, as did earlier ones of similar magnitude. The second factor results in dust lingering at the surface of ice caps that reduced the ability of ice to reflect solar radiation back to space, which enhances summer melting. The third and perhaps most profound factor reduces the formation of ocean bottom water into which dissolved carbon dioxide has accumulated from thermohaline sinking of surface water. This leads to more $CO_2$ in the atmosphere and a growing greenhouse effect. Comforting as finding simplicity within huge complexity might seem, that orbital eccentricity's weak effect on climatic warming – an order of magnitude less than any other astronomical forcing – can tip climate from one extreme to the other should be a grave warning: climate is chaotic and responds unpredictably to small changes …

### Gas hydrates: a warning from the past (*July 2017*)

Detailed sonar imaging above the Troll gas field in the northern North Sea off western Norway has revealed tens of thousands of elliptical pits on the seabed. At around 10 to 20 per square kilometre over an area of about 15,000 km$^2$ there are probably between 150 to 300 thousand of them. They range between 10 to 100 m across and are about 6 m deep on average, although some are as deep as 20 m. They are pretty much randomly distributed but show alignment roughly parallel to regional N-S sea-floor currents. Many of the world's continental shelves display such pockmark fields, but the Troll example is among the most extensive. Almost certainly the pockmarks formed by seepage of gas or water to the surface. However, detailed observations suggest they are inactive structures with no sign of bubbles or fluid seepage. Yet the pits cut though glacial diamictites deposited by the most recent Norwegian Channel Ice Stream through which icebergs once ploughed and which is overlain by thin Holocene marine sediments. One possibility is that they record gas loss from the Troll field, another being destabilisation of shallow gas hydrate deposits.




Parts of the Troll pockmark field off Norway. A: density of pockmarks in an area of 169 square km. B: details of a cluster of pockmarks. (Credit: Mazzini *et al*. 2017; Fig. 1)

Norwegian geoscientists have studied part of the field in considerable detail, analysing carbonate-rich blocks and foraminifera in the pits (Mazzini, A. and 8 others 2017. A climatic trigger for the giant Troll pockmark field in the northern North Sea. *Earth and Planetary Science Letters*, v. **464**, p. 24-34; DOI: 10.1016/j.epsl.2017.02.014). The carbonates show very negative $\delta^{13}C$ values that suggest the carbon in them came from methane, which could indicate either of the two possible means of formation. However, U-Th dating of the carbonates and radiocarbon ages of forams in the marine sediment infill suggest that they formed at around 10 ka ago, 1500 years after the end of the Younger Dryas cold episode and the beginning of the Holocene interglacial. Most likely they represent destabilisation of a once-extensive, shallow layer of methane hydrates in the underlying sediments, conditions during the Younger Dryas having been well within the stability field of gas hydrates. Sporadic leaks from the deeper Troll gas field hosted by Jurassic sandstones are unlikely to have created such a uniform distribution of gas-release pockmarks. Adriano Mazzini and colleagues conclude that rapid early Holocene warming led to sea-floor temperatures and pressures outside the stability field of gas hydrates. There are few signs that hydrates linger in the area, explaining the present inactivity of the pockmarks – all the methane and $CO_2$ escaped before 10 ka.

Gas hydrates are thought to be present beneath shallow seas today, wherever sea-floor sediments have a significant organic carbon content and within the pressure-temperature window of stability of these strange ice-like materials. Mazzini *et al*.'s analysis of the Troll pockmark field has profound implications for the possible behaviour of gas hydrates at a time of global climatic warming. As well as their destabilisation adding to methane release from onshore peat deposits currently locked by permafrost and a surge in global warming, there is an even more catastrophic possibility. The whole of the seaboard of the southern North Sea was swept by a huge tsunami about 8000 years ago, which possibly wiped out Mesolithic human occupancy of lowland Britain, the former land mass of Doggerland in the southern North Sea, and the 'Low Countries' of western Europe. This was created by a massive submarine landslide – the Storegga Slide just to the north of the Troll field – which may have been triggered by destabilisation of submarine gas hydrates during early Holocene warming of the oceans.

## Wildfires and climate at the K-Pg boundary (*September 2017*)

It is now certain that the Cretaceous-Palaeogene boundary 66 Ma ago coincided with the impact of a ~10 km diameter asteroid that produced the infamous Chicxulub crater north of Mexico's Yucatán peninsula. Whether or not this was the trigger for the mass extinction of marine and terrestrial fauna and flora – the flood basalts of the Deccan Traps are still very much in the frame – the worldwide ejecta layer from Chicxulub coincides exactly with the boundary that separates the Mesozoic and Cenozoic Eras. As well as shocked quartz grains, anomalously high iridium concentrations and glass spherules the boundary layer contains abundant elemental carbon, which has been widely ascribed to soot released by vegetation that went up in flames on a massive scale. Atmospheric oxygen levels in the late Cretaceous were a little lower than those at present, or so recent estimates from carbon isotopes in Mesozoic to Recent ambers suggest (Tappert, R. *et al.* 2013. Stable carbon isotopes of C3 plant resins and ambers record changes in atmospheric oxygen since the Triassic. *Geochimica et Cosmochimica Acta, v.* **121**, p. 240-262; DOI: 10.1016/j.gca.2013.07.011). Other estimates put the level substantially above that in modern air. Whatever, global wildfires occurred within the time taken for the Chicxulub ejecta to settle from the atmosphere; probably a few years. It has been estimated that about 700 billion tonnes of soot were laid down, suggesting that most of the Cretaceous terrestrial biomass and even a high proportion of that in soils literally went up in smoke.

Charles Bardeen and colleagues at the University of Colorado, Boulder, have modelled the climatic and chemical effects of this aspect of the catastrophe (Bardeen, C.G. *et al*. 2017. On transient climate change at the Cretaceous−Paleogene boundary due to atmospheric soot injections. *Proceedings of the National Academy of Sciences*, v. **114**, p. E7415-E7424; DOI:

10.1073/pnas.1708980114). Despite the associated release of massive amounts of $CO_2$ and water vapour by both the burning and the impact into seawater, giving increased impetus to the greenhouse effect, the study suggests that fine-grained soot would have lingered as an all enveloping pall in the stratosphere. Sunlight would have been blocked for over a year, so that no photosynthesis would have been possible on land or in the upper ocean. Moreover, the temperatures of the land and ocean surfaces would have dropped by as much as 28 and 11 °C respectively, to cause freezing temperatures at mid-latitudes. Moreover, absorption of solar radiation by the stratospheric soot layer could have increased the temperature of the upper atmosphere by several hundred degrees to destroy the ozone layer. Consequently, once the soot cleared the surface would have had a high ultraviolet irradiation for around a year.

The main implication of the modelling is a collapse in both green terrestrial vegetation and oceanic phytoplankton; the bases of the terrestrial and marine food chains would have been absent for long enough to wipe out those animals that depended entirely on them. While an enhanced greenhouse effect and increased acidification of the upper ocean through $CO_2$ emissions by the Deccan flood volcanism would have placed gradually increasing and perhaps episodic stresses on the biosphere, the outcome of the Chicxulub impact would have been immediate and terrible.

**Volcanism and sea level fall (*September 2017*)**

Most basaltic volcanic activity stems from the rise of hot, deep rock, usually within the mantle. Pressure suppresses partial melting of mantle rock, so as a hot mass rises the greater the chance that it will begin to melt without any rise in its temperature. That is the reason why mantle plumes are associated with many volcanic centres within plates. Extension at oceanic ridges allows upper mantle to rise in linear belts below rift systems giving rise to shallow partial melting, mid-ocean ridge basalts and sea-floor spreading. These aren't the only processes that can reduce pressure to induce such decompression- or adiabatic melting; any means of uplift will do, provided the rate of uplift exceeds the rate of cooling at depth. As well as tectonic uplift and erosion, melting of thick ice sheets and major falls in sea level may result in unloading of the lithosphere.

During Messinian Stage of the late Miocene up to 3 km of evaporitic salt was deposited in the deepest parts of the Mediterranean Basin. One mechanism might have been faster evaporation of seawater than its resupply from the Atlantic through the Straits of Gibraltar, similar to the way in which salt is deposited below the Dead Sea. But the salt layer beneath the modern Mediterranean Sea bed has interleaved riverine sediments containing fossils of land plants. The Straits had closed and the Mediterranean Sea evaporated away. From about 6 to 5.3 Ma ago sea level fell by 3 to 5 km, only returning to normal when the Straits reopened to launch the huge Zanclean flood (watch video simulation), with which the Pliocene of southern Europe and North Africa commenced. A team from the Universities of Geneva, Orleans and Paris and the Instituto de Ciencias de la Tierra Jaume Almera in Barcelona has tested the hypothesis that the Messinian Crisis affected volcanic activity in the area (Sternai, P. *et* al. 2017. Magmatic pulse driven by sea-level changes associated with the Messinian salinity crisis. *Nature Geoscience*, v. **10**, p. 783-787; DOI: 10.1038/ngeo3032).

From the record of salt precipitation, Pietro Sternai and colleagues, reckon that the main phase of unloading of the Mediterranean Basin began at around 5.6 Ma. Allowing for loading by the thick evaporites they calculated that the effect of the loss of water mass was equivalent to an unloading of 15 MPa in the deeper Eastern Mediterranean and 10 MPa in the west. Using standard pressure-temperature melting curves for the upper mantle, they then estimated that any magma chambers affected by the decrease in pressure could yield up to 17% more melt. Radiometrically dated lavas and igneous dykes within the Mediterranean region became more frequent and the number of events more than doubled during the time of main salt deposition.

Stromboli, one of the most active volcanoes in the Mediterranean Basin (credit: Wikipedia)

In May 2017 a study of subglacial volcanoes in West Antarctica based on radar mapping of the solid surface identified 138, 91 of them previously unknown (van Wyk de Vries et al. 2017. A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. *Geological Society, London, Special Publication* **461** ; DOI: 10.1144/SP461.7) They lie within a buried rift system and are covered by thick ice. Only one volcano in Antarctica is known to be active, Erebus, which is part of the cluster. Most of the news items stemming from the publication mentioned the possibility that the buried volcanic tract could be adding to the instability of the West Antarctic Ice Sheet through heating up its base. The WAIS is the ice sheet most feared to collapse seawards leading to a rise of about 3 m in global sea level. If the 2 km thick WAIS did slide off its underlying crust it might possibly trigger reactivation of the volcanic cluster.

### The winter of dinosaurs' discontent (*November 2017*)

Under the auspices of the International Ocean Discovery Program (IODP), during April and May 2016 a large team of scientists and engineers sank a 1.3 km deep drill hole into the offshore, central part of the Chicxulub impact crater, which coincided with the K-Pg mass extinction event. Over the last year work has been underway to analyse the core samples aimed at investigating every aspect of the impact and its effects. Most of the data is yet to emerge, but the team has published the results of advanced modelling of the amount of climate-affecting gases and dusts that may have been ejected (Artemieva, N. *et al*. 2017. Quantifying the release of climate-active gases by large meteorite imp-acts with a case study of Chicxulub. *Geophysical Research Letters*, v. **44**; DOI: 10.1002/2017GL074879). Petroleum exploration in the Gulf of Mexico reveals the impact site to have been underlain by about 2.5 to 3.5 km of Mesozoic sediments that include substantial amounts of limestones and evaporitic anhydrite ($CaSO_4$) – thicknesses of each are of the order of a kilometre. The impact would inevitably have yielded huge volumes of carbon- and sulfur dioxide gases, as well as water vapour plus solid and molten ejecta. The first, of course, is a critical greenhouse gas, whereas $SO_2$ would form sulfuric acid aerosols if it entered the stratosphere. They are known to block incoming solar radiation. So both warming and cooling influences would have been initiated by the impact. Dust-sized ejecta that lingered in the atmosphere would also have had climatic cooling effects. The questions that the study aimed to answer concerns the relative masses of each gas that would have reached more than 25 km above the Earth to have long-term, global climatic effects and whether the dominant effect on climate was warming or cooling. Both gases would have added the environmental effects of making seawater more acid.

Such estimates depend on a large number of factors beyond the potential mass of carbonate and sulfate source rocks. For instance: how big the asteroid was; how fast it was travelling and the angle at which it struck the Earth's surface determine the kinetic energy involved and the impact mechanism. How that energy was distributed between atmosphere, seawater and the sedimentary sequence, together with the pressure-temperature conditions for the dissociation of calcite and anhydrite all need to be accounted for by modelling. Moreover, the computation itself becomes extremely long beyond estimates for the first second or so of the impact. Earlier estimates had been limited by computer speeds to only the first few seconds of the impact and could not allow for other than vertical impacts. The new study, by supercomputers and improved algorithms, used a likely 60° angle of impact, new data on mineral decomposition and simulated the first 15 to 30 seconds. The results suggested that 325 ± 130 Gt of sulfur and 425 ± 160 Gt $CO_2$ were ejected, compared with earlier estimates of 40-560 Gt of sulfur and 350-3,500 Gt of $CO_2$. The greater proportion of sulfur release to the stratosphere pushes the model decisively towards global cooling, probably over a lengthy period – perhaps centuries. Taking dusts into account implies that visible sunlight would also have been blocked, devastating the photosynthetic base of the global food chain, in the sunlit parts of oceans as well as on land.

But we have to remember that these are the results of a theoretical model. In the same manner as this study has thrown earlier modeling into doubt, more data – and there will be a great many from the Chicxulub drill core itself – and more sophisticated computations may change the story significantly. Also, the other candidate for the mass extinction event – the flood basalt volcanism of the Deccan Traps – and its geochemical effects on the climate have yet to be factored in. The next few lines of Shakespeare's soliloquy for Gloucester in *Richard III* may well emerge from future work

> *… Made glorious summer by this sun of York;*
> *And all the clouds that lour'd upon our house*
> *In the deep bosom of the ocean buried …*

**See also:** BBC News comment on 31 October 2017