Climate change and palaeoclimatology

Reconstructing the structure of ancient vegetation canopies (*January 2015*)

One of the central measures used to describe modern ecosystems is the ratio of foliage area to that of the ground surface – the leaf area index (LAI) – which expresses the openness of vegetation canopies. A high LAI helps to retain moisture in the soil, partly by shading and cooling the surface to reduce evaporation and partly by stopping surface soil from being battered to a concrete-like consistency by heavy rain, which reduces the amount of water that can infiltrate. It is possible to estimate LAI across today's entire land area using satellite image data but a proxy for palaeoecological LAI has remained hard to find.

Hemispherical photograph used to calculate modern canopy cover. (credit: Wikipedia; photo by S.B. Weiss)

The outer coating of leaves in well-shaded (high LAI) areas tends to have protective or pavement cells that are larger and have more complicated shapes than does that of leaves in more open canopies. The framework of leaf cells is silica-based and made up of structures known as phytoliths whose morphologies vary in much the same way as the cells that they support. So theoretically it is possible to use fossil phytoliths in terrestrial sediments to estimate LAI variations through time in local canopies, but first the approach needs a means of calibration from living ecosystems. The vegetation of Central American Costa Rica varies through the entire range of possible LAI values, which leads to varying amounts of sunlight available to the leaves of cover plants. Measuring the area and the degree of shape-complexity of phytoliths in modern soils there shows that each is positively correlated with LAI.

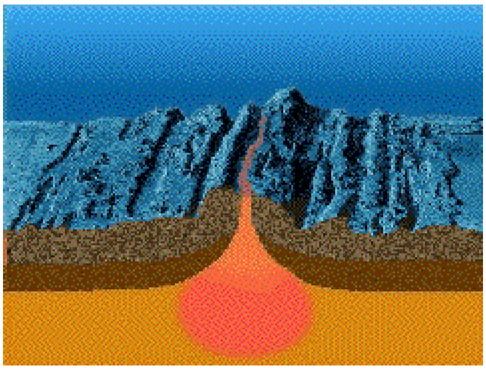
A modern herbivorous mammal (lowland paca) from dense forest in Costa Rica. (Photo credit: Wikipedia)

Putting this approach to use in the Cenozoic terrestrial sediments of Patagonia, US and Argentinean palaeoecologists aimed to examine how the evolution of the teeth of herbivorous mammals – a major feature in their speciation – linked to changes in vegetation structure (Dunn, R.E. *et al*. 2015. Linked canopy, climate and faunal change in the Cenozoic of Patagonia. *Science*, v. **347**, p. 258-261; DOI: 10.1126/science.1260947). Using phytoliths they were able to show that in the Eocene the area was covered by dense, closed forest canopies that gradually became more open towards the end of the Eocene to be replaced by open forest and shrubland habitats in the Oligocene and Miocene, with a brief period of regreening. It was during the period of more open vegetation that tooth structure underwent the most change. Chances are that the vegetation shifts began in response to the onset of Antarctic glaciation at the beginning of the Oligocene Epoch and related climate change at the northern margin of the Southern Ocean. Changes in the herbivore teeth may have been in response to the increasing amount of dust adhering to leaves as canopies became more open and soil increasingly dried out.

Glacial cycles and sea-floor spreading (*February 2015*)

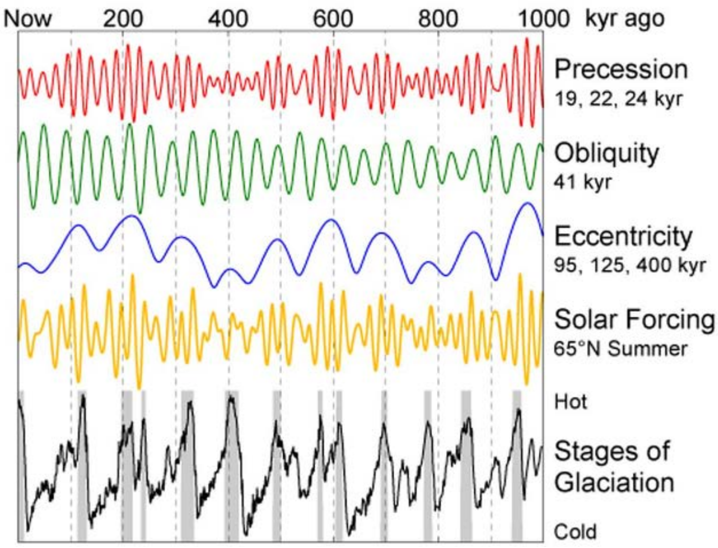
The *London Review of Books* recently published a lengthy review (Godfrey-Smith, P. 2015. The Ant and the Steam Engine. *London Review of Books*, v. **37**, 19 February 2015 issue, p. 18-20) of the latest contribution to Earth System Science by James Lovelock, who created that popular paradigm through his Gaia concept of a self-regulating Earth (Lovelock, J. *A Rough Ride to the Future*. Allen Lane: London; ISBN 978 0 241 00476 0). Coincidentally, on 5 February 2015 *Science* published online a startling account of the synergism of Earth processes and climate (Crowley, J.W. *et al*. 2015. Glacial cycles drive variations in the production of oceanic crust. *Science*, v. 347, p. 1237-1240; DOI: 10.1126/science.1261508). In fact serendipity struck twice: the following day a similar online article appeared in a leading geophysics journal (Tolstoy, M. 2015. Mid-ocean ridge eruptions as a climate valve. *Geophysical Research Letters*, v. **42**, p. 1346-1351; DOI: 10.1002/2014GL063015)

Both articles centred on the most common topographic features on the ocean floor, abyssal hills. These linear features trend parallel to seafloor spreading centres and the magnetic stripes, which chart the progressive additions to oceanic lithosphere at constructive margins. Abyssal hills are most common around intermediate- and fast-spreading ridges and have been widely regarded as fault-tilt blocks resulting from extensional forces where cooling of the lithosphere causes it to sag towards the abyssal plains. However, some have suggested a possible link with variations in magma production beneath ridge axes as pressure due to seawater depth varied with rising and falling sea level through repeated glacial cycles. Mantle melting beneath ridges results from depressurization of rising asthenosphere: so-called 'adiabatic' melting. Pressure changes equivalent to sea-level fluctuations of around 100-130 m should theoretically have an effect on magma productivity, falls resulting in additional volumes of lava erupted on the ocean floor and thus bathymetric highs.



Animation of ocean ridge formation, showing parallel topography and magnetic reversals (Credit: USGS).

A test of this hypothesis would be see how the elevation of the sea floor adjacent to spreading axes changes with the age of the underlying crust. John Crowley and colleagues from Oxford and Harvard Universities and the Korea Polar Research Institute analysed new bathymetry across the Australian-Antarctic Ridge, whereas Maya Tolstoy of Columbia University performed similar work across the Southern East Pacific Rise. In both studies frequency analysis of changes in bathymetry through time, as calibrated by local magnetic stripes, showed significant peaks at roughly 23, 41 and 100 ka in the first study and at 100 ka in the second. These correspond to the well known Milankovitch periods due to precession, changing axial tilt and orbital eccentricity: persuasive support for a glacial control over [mid-ocean ridge](#) magmatism..

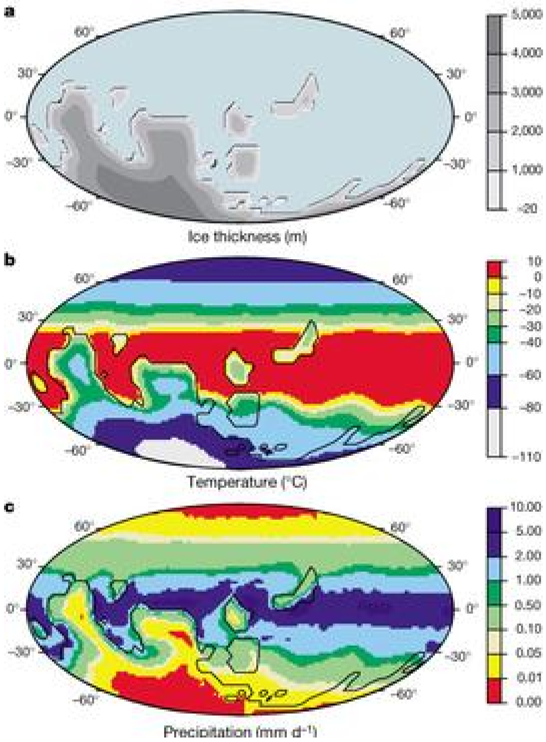


Periodicities of astronomical forcing and global climate over the last million years (credit: Wikipedia)

An interesting corollary of the observations may be that pulses in sea-floor eruption rates emit additional carbon dioxide, which eventually percolates through the ocean to add to its atmospheric concentration, which would result in climatic warming. The maximum effect would correspond to glacial maxima when sea level reached its lowest, the reduction in pressure stimulating the greatest magmatism. One of the puzzling features of glacial cycles over the last million years, when the 100 ka eccentricity signal dominates, is the marked asymmetry of the sea-level record; slowly declining to a glacial maximum and then a rapid rise due to warming and melting as the Earth changed to interglacial conditions. Atmospheric CO_2 concentrations recorded by bubbles in polar ice cores show a close correlation with sea-level change indicated by oxygen isotope data from oceanic sediments. So it is possible that build-up of polar ice caps in a roundabout way eventually reverse cooling once they reach their greatest thickness and extents, by modulating ocean-ridge volcanism and thereby the greenhouse effect.

Related articles: Ice ages made Earth's ocean crust thicker (nature.com)

Snowball Earth events pinned down (*May 2015*)



Computer simulation of conditions during a Snowball Earth period. (Credit: Hyde et al., 2000. *Nature* v. **405**, p. 425-429,)

The Cryogenian Period that lasted from 850 to 635 Ma ago takes its name from evidence for two and perhaps three episodes of glaciation at low latitudes. It has been suggested that, in some way, they were instrumental in the decisive stage of biological evolution from which metazoan eukaryotes emerged: the spectacular Ediacaran fossil assemblages (see *Bigging up the Ediacaran* March 2011) follow on the heels of the last such event. Although controversies about the reality of tropical latitudes experiencing ice caps have died away, there remains the issue of synchronicity of such frigid events on all continents, which is the central feature of so-called 'Snowball Earth' events. While each continent does reveal evidence for two low latitude glaciations – the Sturtian (~710 Ma) and the later Marinoan (~635 Ma) – in the form of diamictites (sediments probably dropped from floating ice and ice caps) it has proved difficult to date their start and duration. That is, the cold episodes may have been diachronous – similar conditions occurring at different localities at different times. Geochronology has, however, moved on since the early disputes over Snowball Earths and more reliable and precise dates for beginnings and ends are possible and have been achieved in several places (Rooney, A.D. *et al*. 2015. A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations.. *Geology*, v. **43**, p. 459-462; DOI: 10.1130/G36511.1).

Rooney and colleagues from Harvard and the University of Houston in the USA used rhenium-osmium radiometric dating in Canada, Zambia and Mongolia. The Re-Os method is especially useful for sulfide minerals as in the pyritic black shales that occur extensively in the Cryogenian, generally preceding and following the glacial diamictites and their distinctive carbonate caps. Combined with a few ages obtained by other workers using the Re-Os method and U-Pb dating of volcanic units that fortuitously occur immediately beneath or within diamictites, Rooney *et al*. establish coincident start and stop dates and thus durations of both the Sturtian and Marinoan glacial events: 717 to 660 Ma and 640 to 635 Ma respectively on all three continents. Their data is also said to refute the global extent and even the very existence of an earlier, Kaigas glacial event (~740 Ma) previous recorded from diamictites in Namibia, the Congo, Canada and central Asia. This assertion is based on the absence of diamictites with that age in the area that they studied in Canada and their own dating of a diamictite in Zambia, which is one that others assigned to the Kaigas event

The dating is convincing evidence for global glaciation on land and continental margins in the Cryogenian, as all the dates are from areas based on older continental crust. But the concept of Snowball Earth, in its extreme form, is that the oceans were ice-capped too as the name suggests, which remains to be convincingly demonstrated. That would only be achieved by suitably dated diamictites located on obducted oceanic crust in an ophiolite complex. Moreover, there are plenty more Cryogenian diamictites on other palaeo-continents and formed at different palaeolatitudes that remain to be dated (see *And now another blow for 'Snowball Earth* October 2006)

Flourishing life during a Snowball Earth period (*June 2015*)

That glacial conditions were able to spread into tropical latitudes during the late Neoproterozoic, Cryogenian Period is now well established, as are the time spans of two such events (see previous entry). But what were the consequences for life that was evolving at the time? That something dramatic was occurring is signalled by a series of perturbations in the carbon-isotope composition of seawater. Its relative proportion of ^{13}C to ^{12}C ($\delta^{13}C$) fell sharply during the two main Snowball events and at other times between 850 to 550 Ma. Since ^{12}C is taken up preferentially by living organisms, falls in $\delta^{13}C$ are sometimes attributed to periods when life was unusually suppressed. It is certain that the 'excursions' indicate that some process(es) must have strongly affected the way that carbon was cycled in the natural world.

The further sea ice extended beyond landmasses during Snowball events the more it would reduce the amount of sunlight reaching the liquid ocean and so photosynthesis would be severely challenged. Indeed, if ice covered the entire ocean surface – the extreme version of the hypothesis – each event must have come close to extinguishing life. An increasing amount of evidence, from climate- and oceanographic modelling and geological observation, suggests that a completely icebound Earth was unlikely. Nevertheless, such dramatic climate shifts would have distressed living processes to the extent that extinction rates were high and so was adaptive radiation of survivors to occupy whatever ecological niches remained or came into being: evolution was thereby speeded up. The roughly half-billion years of the Neoproterozoic hosted the emergence and development of multicellular organisms (metazoan eukaryotes) whose cells contained a nucleus and other bodies such as mitochondria and the chloroplasts of photosynthesisers. This hugely important stage of evolution burst forth shortly after the last Snowball event; during the Ediacaran and the Cambrian Explosion. But recent investigations by palaeontologists in glaciogenic rocks from China unearthed a rich diversity of fossil organisms that thrived *during* a Snowball event (Ye, Q. *et al*. 2015. The survival of benthic macroscopic phototrophs on a Neoproterozoic snowball Earth. *Geology*, v. **43**, p. 507-510; DOI: 10.1130/G36640.1).

The Nantuo Formation in southern China contains glaciogenic sedimentary rocks ascribed to the later Marinoan glaciation (640 to 635 Ma). Unusually, the pebbly Nantuo glaciogenic rocks contain thin layers of siltstones and black shales. The fact that these layers are free of coarse fragments that floating ice may have dropped supports the idea that open water did exist close to glaciated landmasses in what is now southern China. Palaeomagnetic measurements show that the area was at mid-latitudes during the Marinoan event. The really surprising feature is that they contain abundant, easily visible fossils in the form of carbonaceous ribbons , disks, branching masses and some that dramatically resemble complex multi-limbed animals, though they are more likely to be part of an assemblage of algal remains. Whatever their biological affinities, the fossils clearly signify that life happily flourished beneath open water where photosynthesis provided a potential base to a food chain, though no incontrovertible animals occur among them.

Related articles:

See also: Corsetti, F.A. 2015. Life during Neoproterozoic Snowball Earth. *Geology*, v. **43**, p. 559-560; DOI: 10.1130/focus062015.1; Fossils Explain How Life Coped During Snowball Earth (spacedaily.com)

Are coral islands doomed by global warming? (*June 2015*)

Among the most voluble and persistent advocates of CO_2 emissions reduction are representatives of islands in the tropics that are built entirely of reef coral. The habitable land on them reaches only a few metres above high-tide level, so naturally they have far more cause to worry about global warming and sea-level rise than most of us. Towns and villages on some atolls do seem to be more regularly inundated than they once were. So a group of scientists from New Zealand and Australia set out to check if there have been losses of land on one Pacific atoll, Funafuti in Tuvalu, during the century since tidal observatories first recorded an average 1.7 mm annual rise in global sea level and a faster rate (~3 mm a^{-1}) since 1993 (Kench, P.S. *et al*. 2015. Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, v. **43**, p.515-518; DOI: 10.1130/G36555.1).

Funafuti atoll (Tuvalu) from space

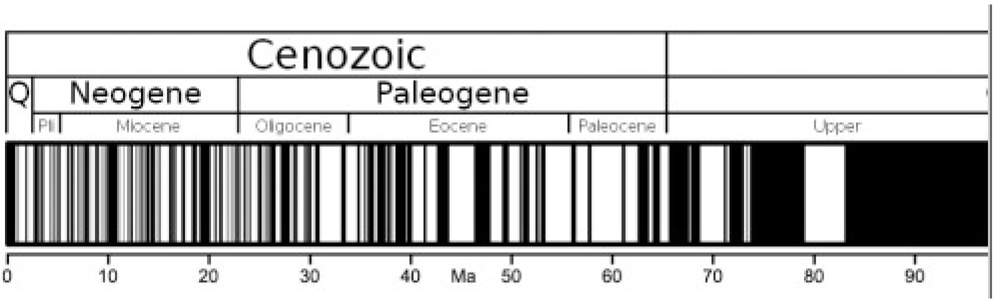
Funafuti atoll comprises 32 islands that make up its rim, with a range of sizes, elevations, sediment build-ups and human modifications. The atoll was first accurately surveyed at the end of the 19th century, has aerial photographic cover from 1943, 1971 and 1984 and high-resolution satellite image coverage from 2005 and 2014, so this is adequate to check whether or not sea-level rise has affected the available area and shape of the habitable zone. It appears that there has been no increase in erosion over the 20th century and rather than any loss of land there has been a net gain of over 7%. The team concludes that coral reefs and islands derived from their remains and debris are able to adjust their size, shape and position to keep pace with sea level and with the effects of storms.

Beach on Fongafale Islet part of Funafuti Atoll, Tuvalu. (Credit: Wikipedia)

This is an observation of just one small community in the vastness of the Pacific Ocean, so is unlikely to reassure islanders elsewhere who live very close to sea level and are anxious. It is a finding that bears out longer-term evidence that atolls remained stable during the major sea-level changes of the post-glacial period until about 7 thousand years ago when land glaciers stabilised. Since coral grows at a surprisingly rapid rate, that growth and the local redistribution of debris released by wave action keep pace with sea-level change; at least that taking place at rates up to 3 mm per year. But the study leaves out another threat from global warming. Corals everywhere are starting to show signs of ill thrift, partly resulting from increasing acidity of seawater as more CO_2 dissolved in it and partly from increases in sea-surface temperature, as well a host of other implicated factors. This manifests itself in a phenomenon known as coral bleaching that may presage die-off. Should coral productivity decrease in the Pacific island states then the material balance shifts to land loss and sea level will begin an irresistible threat.

The core's influence on geology: how does it do it? (*November 2015*)

Although no one can be sure about the details of processes in the Earth's core, what is accepted by all is that changes in core dynamics cause the geomagnetic field to change in strength and polarity, probably through some kind of physical interaction between core and deep mantle at the core-mantle boundary (CMB). Throughout the last 73 Ma and especially during the Cenozoic Era geomagnetism has been more fickle than at any time since a more or less continuous record began to be preserved in the Jurassic to Recent magnetic 'stripes' of the world ocean floor. Moreover, they came in bursts: 5 in a million years at around 72 Ma; 10 in 4 Ma centred on 54 Ma; 17 over 3 Ma around 42 Ma; 13 in 3 Ma at ~24 Ma; 51 over a period of 12 Ma centring on 15 Ma. During the Late Jurassic and Early Cretaceous the core was similarly 'busy', the two time spans of frequent reversals being preceded by quiet 'superchrons' dominated by the same normal polarity as we have today i.e. magnetic north being roughly around the north geographic pole.



The Cenozoic history of magnetic reversals – black periods were when geomagnetic field polarity was normal and white when reversed. (credit: Wikipedia)

Until recently geomagnetic 'flips' between the two superchrons were regarded as random , perhaps suggesting chaotic behaviour at the CMB. But such a view depends on the statistical method used. A novel approach to calculating reversal frequency through time, however, shows peak-trough pairs recurring 5 times through the Cenozoic Era, approximately 13 Ma apart: maybe the chaos is illusory (Chen, J. *et al*. 2015. The 13 million year Cenozoic pulse of the Earth. *Earth and Planetary Science Letters*, v. **431**, p. 256-263; DOI: 10.1016/j.epsl.2015.09.033). So, here is a kind of yardstick to see if there may be any connection between core processes and those at the surface, which Chen of the Fujian

Normal University, Fushou China and Canadian and Chinese colleagues compared with the very detailed Cenozoic oxygen-isotope ($\delta^{18}O$) record preserved by foraminifera in ocean-floor sediments, which is a well established proxy for changes in climate. Removing the broad trend of cooling through the Cenozoic resulted in a plot of more intricate climatic shifts that matches the geomagnetism record in both shape and timing of peak-trough pairs. It also turns out, or so the authors claim, that both measures correlate with changes in the rate of Cenozoic subduction of oceanic lithosphere (a measure of plate tectonic activity), albeit negative – peaks in magnetism and climate connecting with slowing in the pace of tectonics.

The analyses involved some complicated maths, but taken at face value the correlations beg the questions why and how? Long-term climate change contains an astronomical signal, encapsulated in the Milankovich hypothesis which has been tested again and again with little room for refutation. So is this all to do with gravitational influences in the Solar System. More exotic still is the possibility of 13 Ma cyclicity linking the Milankovich mechanism with the vaster scale of the Sun's orbit oscillating through the disc of the Milky Way galaxy and theoretical hints of a mysterious role for dark matter in or near the galaxy. Or, is it a relationship in which climate and the magnetic field are modulated by plate tectonics through varying volcanic emissions of greenhouse gases and the deep effect of subduction on processes at the CMB respectively? To me that seems more plausible, but it is still as exceedingly complex as the maths used to reveal the correlations.

Paris Agreement 2015: Carbon Capture and Storage (*December 2015*)

Anyone viewing news that covered the adoption of the Paris Agreement on climate change on 11 December 2015 would have seen clear evidence of the reality of the old saw, 'There was dancing in the streets'. Not since the premature celebration of the landing of the Philae spacecraft on comet 67P/Churyumov–Gerasimenko, 11 months before, has there been such public abandonment of normal human restraint. In the case of 'little Philae' the object of celebration sputtered out three days after landing, albeit with the collection of some data. Paris 2015 is a great deal more important: the very health of our planet and its biosphere hangs on its successful implementation. At 32 pages long, by UN standards the document agreed to by all 196 UN Member States is pretty succinct considering everything it is supposed to convey to its signatories and the human race at large.

One central and, by most scientific criteria, the most important technology needed as a stopgap before the longed-for adoption of carbon-free energy generation does not figure in the diplomatic screed: carbon capture and storage (CCS) is not mentioned once. Indeed, only 10 Member States have included it in their pledge or 'intended nationally determined contribution' (INDC) – Bahrain, Canada, China, Egypt, Iran, Malawi, Norway, Saudi Arabia, South Africa and the United Arab Emirates. Only three of them are notable users of coal-fired power stations for which CCS is most urgent. An article in the January 2016 issue of Scientific American offers an explanation of what seems to be a certain diplomatic timidity about this highly publicized stop-gap measure (Biello, D. 2016. The carbon capture fallacy. *Scientific American*, v. **314**(1) 55-61; DOI: 10.1038/scientificamerican0116-58). David Biello emphasizes the urgency of CCS from more industries than fossil fuel power plants, cement manufacture being a an example. He focuses on the economics and logistics of one of very few CCS facilities that may be on track for commissioning (33 have been shut down or cancelled worldwide since 2010).

The Bagger 288 bucket wheel reclaimer (the world's largest land vehicle) moves from one lignite mine to another in Germany to add more CO_2 to the atmosphere.

The Kemper power station in Mississippi, USA is the most advanced in the US, as it has to be to burn the strip-mined, wet, brown coal or lignite that is its sole fuel. The chemistry it deploys is quite simple but technologically complex and expensive. So Kemper survives only because it aims to sell the captured CO_2 to a petroleum company so that it can be pumped into oil fields to increase dwindling production. However, its extraction costs US$1.50 t^{-1}, while naturally occurring, underground CO_2 costs US$0.50 t^{-1} to pump out. Moreover, Kemper's power output at US$11 000 per kW of generating capacity is three times more expensive than that for a typical coal-fired boiler. Mississippi Power is lucky, in that it only needs to pipe the gas 100 km to its 'partner' oil field; a pretty small one producing about 5000 barrels per day. Some coal plants are near oil fields, but the majority are not. To cap it all, only about a third of the CO_2 production is likely to remain in long-term underground storage.

Because Kemper has, predictably, hit the financial buffers (almost US$4 billion over budget) to avoid bankruptcy it has raised electricity prices to its customers by 18%. Without the projected revenue from its partnered oil field it would go belly up. Even in the happy event of financial break-even, in carbon terms it would be subsidising the oilfield to produce…CO_2! But the sting in the tail of Biello's account of this 'flagship' project is that the plant is currently neither burning coal nor capturing carbon: it uses natural gas…