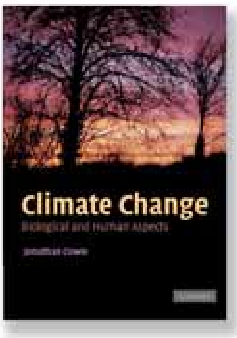


Beyond *the*

Climate change has happened before in the geological past. Much work has focused on the Quaternary but, Jonathan Cowie asks, should we now be looking more at the Eocene and Toarcian?*

***Jonathan Cowie** is the author of *Climate Change: Opportunity of Disaster?* (1998) the basis of which was the core theme of the 2006 Stern Report. Cambridge University Press has just published his latest climate book, *Climate Change: Biological and Human Aspects*.

We have long known that the Earth has previously been warmed, and cooled, by changes in atmospheric carbon-based and other greenhouses gases. Considerable attention has in recent decades focused on both the geology and biology of Quaternary rather than older strata. Indeed, one area of geological work - ice core analysis - has only provided a highly detailed look at atmospheric composition and regional temperature going back some 400,000 years: this record is currently held by the European Project for Ice Coring in Antarctica (EPICA, 2004).

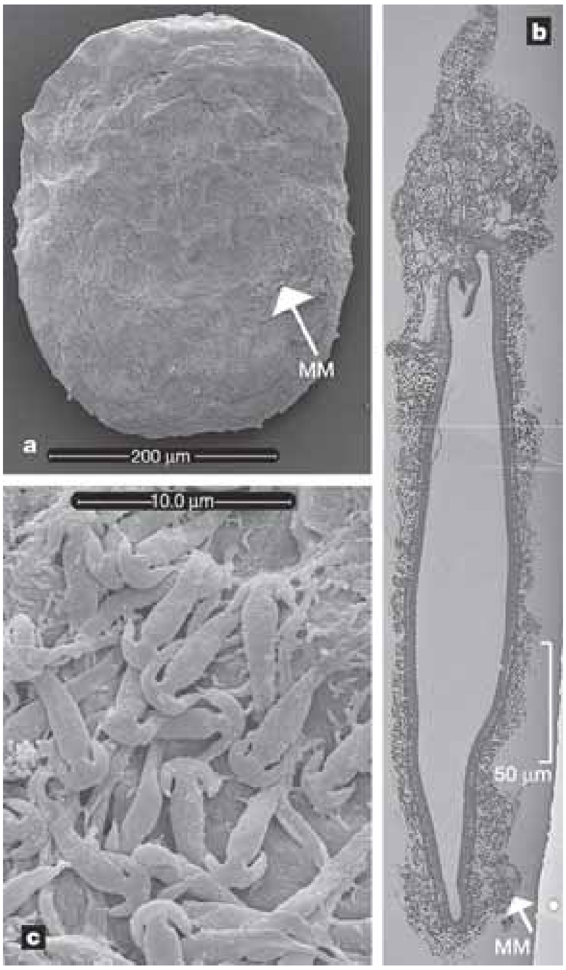
However while regional temperature changes of around 6°C have been inferred from Quaternary ice cores, these actually relate to glacial-interglacial climate oscillations - from around present-day temperatures to cooler climate regimes in the past, and not to future warmer ones. Furthermore, because previous interglacials were only just one degree or so warmer than today at most (ref. pt. 1990), it is almost certain – if the Intergovernmental Panel on Climate Change (IPCC, 2007) is right – that the 21st Century will see this limit exceeded and an average global temperature not seen on Earth since the Pliocene or earlier. If we are to find palaeo-analogues to the late 21st Century greenhouse world, then it will have to be a warmer analogue prior to the Quaternary. Such analogues exist. Indeed, examples caused by bursts of carbon into the atmosphere are known. The only difference is that these releases of greenhouse gas were, of course, natural.

Early Eocene

The most recent and best understood of these episodes took place some 55 million years ago (Ma) at the beginning of the Eocene, marked by the 'Palaeocene-Eocene Thermal Maximum' or 'Initial Eocene Thermal Maximum' (PETM or IETM). The ^{18}O isotope record firmly suggests that the early Eocene had warm oceans. There is also ample evidence it was also warm on land. Plant fossils consistently show that species (or relatives of species) currently found at tropical latitudes were then found at higher latitudes, even after allowing for plate motions.

For example in the early Eocene, at palaeolatitudes of 47° that today sport temperate biomes, we find the highly diverse sub-tropical ones. Early Eocene tropical rain forests extended in places as far north as 45°. The modern equivalent latitude is as far north as Bordeaux in France or Bangor (Maine) in the USA: though of course there is more to climate than latitude alone. Britain at the time was covered in tropical forest and palm trees grew as far north as Alaska.

That the greenhouse world into which we are heading is not unique does not mean that we need not worry about global warming. Such periods occurred millions of years before humans, or our modern assemblage of species, evolved. Ecologically our likely greenhouse future will pose a threat to these systems. Also, although the planet has been much warmer in the past, what is new to our understanding in the past couple of decades is just how anomalous the early Eocene was compared to the time immediately beforehand (56Ma) and immediately after (54Ma).



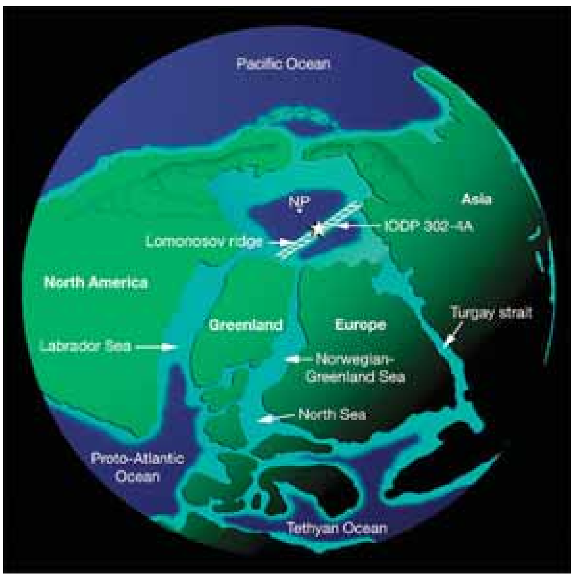
Azolla spores ©Henk Brinkhuis

fridge

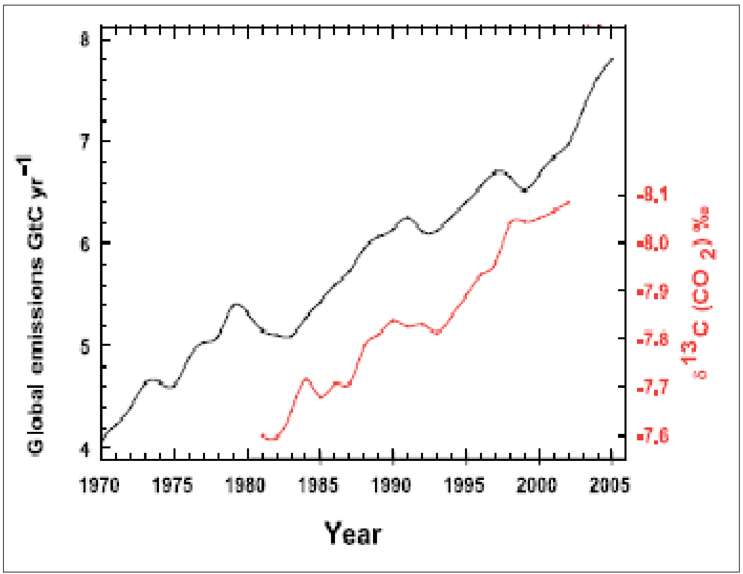
Eocene polar regions

Today, as we look to our likely greenhouse future, there is considerable ecological concern over circum-polar habitats and species. We are already seeing evidence of permafrosts thawing and mega-fauna populations, such as polar bears, are (we are told) under stress. So what was the Arctic like in the early Eocene?

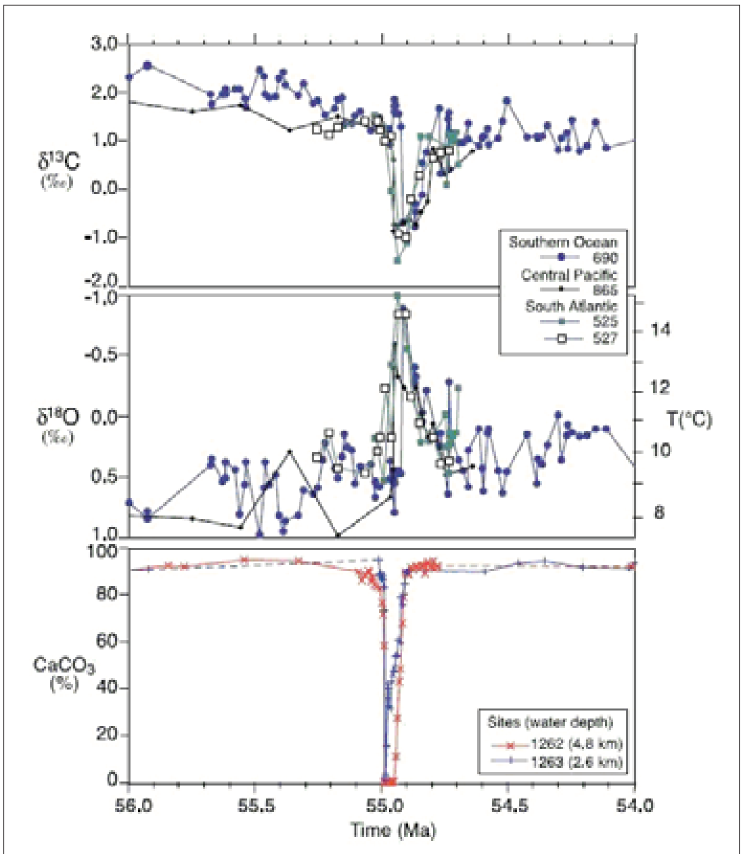
We have ample evidence from all continents (other than Antarctica) and ocean sediments about early Eocene conditions, but until very recently there was nothing to tell us what it was like near the North Pole. Until as recently as 2004 the palaeoceanographic sediment record for the central Arctic only went as far back as 500,000 years. A similar length of time was covered by the Antarctic ice-core record. However sediment cores extracted in August 2004 as part of the Integrated Ocean Drilling Program Arctic Coring Expedition (IOCDP ACEX) were first laid down as long ago as 65Ma. These records marked a major scientific break-through – and results were first published in three papers in *Nature* on 1 June last year. The results not only corroborated evidence from lower latitudes about just how warm the Earth must have been in the early Eocene, but suggested



The Eocene world



Annual averages of the 13C/12C ratio measured in atmospheric CO2 at Mauna Loa from 1981 to 2002 (red) are also shown (Keeling et al, 2005). The isotope data are expressed as 13C(CO2) ‰ (per mil) deviation from a calibration standard. Note that this scale is inverted to improve clarity. Source IPCC 2007



that the 55Ma episode marked possibly the warmest time at the North Pole for over 100My: certainly it has not been as warm since. Today's circum-polar ecosystems could not exist in such a climate regimen.

Perhaps the most staggering result was evidence that at times during the early Eocene warm episode the Arctic sea surface temperature soared to 24°C. Then the typically warm water dinoflagellate genus *Apectodinium* dominated the fossil record. Also at certain times during this warm phase the freshwater fern *Azolla* flourished. Of course, the Eocene Arctic ocean was a lot smaller than it is today, and had only three narrow connections to the world ocean. Consequently freshwater run-off allowed brackish and even freshwater flora to flourish. *Azolla* tolerates salinities of up to 5.5‰ but nothing higher than 1- 1.6‰ (average marine salinity today is 34.72‰). Those working in the oil industry have long reported (though not in available peer-reviewed literature) *Azolla* from early-Eocene cores taken by oil rigs in the Nordic seas; what is new is that this species also flourished much further north.

Causes

So, what caused the planet to heat up and how long did the warm period last? The ^{12}C:^{13}C carbon isotope excursion (CIE) found in early Eocene strata, as well as ^{18}O analysis, gives us a good idea.

Biogenic sources of carbon contain less of the minority ^{13}C isotope compared to non-biogenic sources. This is because photosynthesis discriminates in favour of ^{12}C. Consequently, if the ratio of ^{13}C in sediments decreases at any time then there must be even more ^{12}C than before, diluting it further. The implication is that biogenic carbon must be the source of this extra ^{12}C.

If we know the ratios of ^{13}C to ^{12}C before, during and after a carbon isotope excursion event (CIE), and we have an idea of how much carbon there is in the atmosphere and (broadly) in other biosphere pools, then we can calculate how much ^{12}C must have been released into the atmosphere in order to end up as carbonate ($CO_3^{-\,-}$) and other forms in sediments. Fortunately there are plenty of places where carbon was laid down before, during and after this early Eocene warming event, so it is possible to make a broad-brush estimate as to how much ^{12}C was released globally. These estimates all tend to be in the range of 1200 - 5000 GtC (gigatonnes carbon) with 2000 GtC often cited.

Knowing that there was a warm episode back in the early Eocene is one thing. Knowing that there was an anomalous carbon isotope excursion is another. Being confident that these were connected in the form of a pulse of carbon dioxide is something else.

One possible source of the CO_2 could have been the combustion of plants and trees. But as the planet currently supports c. 1840 gigatonnes of dry terrestrial biomass then all would need to be burned to account for the excursion. How about a carbonaceous chondrite impacting the Earth? Alas, if one had, we would expect to see an iridium peak in early Eocene sediments. Three other possibilities remain. A major fossil fuel seam may have ignited. Marine methane hydrates may have destabilised, releasing a massive amount of methane. Or, both possibilities occurred.

Methane hydrates (clathrates) form under pressure from methane combining into a complex with water. There are vast amounts of methane clathrate at certain depths in the ocean, created by decomposition of the rain of plankton and other organic material in areas where life flourishes.

However if a major ignition of fossil fuel had occurred, then marine methane hydrate would almost certainly have destabilised as well. This too would have contributed to the CIE. Also, methane hydrate does not decompose *en masse* without some trigger.
So we have a possible theoretical trigger for the event. Where is the smoking gun? In 2004 Henrik Svensen and his Norwegian team found thousands of hydrothermal vents under the Norwegian Sea that could have been created by gas being driven off from heated organic-rich strata beneath. The North Atlantic 'large-scale igneous province' was active around this time, so a compelling prospect opens up that igneous activity may have ignited organic-rich strata and resulted in a release of greenhouse

gas sufficient to warm the planet by a few degrees. Oceans warmed as a result, destabilising marine methane hydrates. This then warmed the planet even further - for the time required for the biosphere's carbon pools to re-adjust: namely, about 100,000 - 200,000 years. And that is, in fact, the timescale of the Eocene warming (see figure).

Back to the Eocene?

The Svensen team (2004) ventured that 6.3 gigatonnes of carbon might have been released from the incursion from the North Atlantic Volcanic Province over 35 - 360 years. Interestingly, around 6.0 GtC compares well with the amount of the anthropogenic carbon released each year throughout the 1990s. If this carbon incursion did trigger the early Eocene warming, then humanity may already have pushed the global climate system sufficiently to trigger similar methane destabilisation. Corroborating evidence that the volcanic province was the initial trigger came last spring, from volcanic ash dates coinciding closely with the warming event.

So why have we not yet seen massive marine methane hydrate destabilisation? The answer is quite simple. While we have, through deforestation and fossil fuel combustion, set climate change in motion, the planet has not quite warmed up enough, and the heat not sufficiently penetrated the oceans, to initiate such a destabilisation. But we know that even if, by some magic, we stopped *all* fossil fuel combustion tomorrow, then the Earth would still continue to warm through to the end of the Century. If every nation fully adopted the Kyoto aspiration, then the Earth would continue to warm during the 22nd Century.

Current atmospheric carbon dioxide concentrations, at over 380ppm, already exceed the peak level of carbon dioxide during past interglacials that we have measured (from air bubbles trapped in ice cores by the European Project for Ice Coring in Antarctica (EPICA) going back over 400,000). Consequently, even though the full climate impact of this greenhouse 'climate forcing' has not yet become manifest, it has been delivered.

When might we expect to see massive methane hydrate dissociation? This is a good question but (currently) a complete unknown. One thing we do know is that it is unlikely to be before the Earth warms in excess of the last glacial maximum; we may therefore have a few decades of complete safety left to us, at the very least. Second, given that oceanic mixing times are in the order of centuries, it may be we have a few *centuries* to go at the most. (Though remember: the first 300m or so of the ocean have already begun to warm - the fuse is lit.)

IPCC 2007 and future science

The IPCC 2007 Assessment skates around the early Eocene-analogue issues. Its chapter on palaeoclimates does have a subsection on the early Eocene and the chapter on the atmosphere does cover the present CIE due to fossil fuel release and deforestation. However otherwise the IPCC do not connect the two. The closest it comes to making a definitive statement on the Eocene event as an analogue is:

"Although there is still too much uncertainty in the data to derive a quantitative estimate of climate sensitivity from the PETM [Palaeocene Eocene Thermal Maximum], the event is a striking example of massive carbon release and related extreme climatic warming."

Clearly the implications for future research are considerable. Research into the biosphere processes of the early Eocene (or the Toarcian, another CIE event) simply has not had anything like the multi-million pound investment that other areas of climate science have been afforded. If it is not in the literature then it is not in the IPCC assessments. However now that those few scientists who have worked on the Eocene (and Toarcian) have done enough to demonstrate that past CIEs events very likely represent palaeoanalogues to the warming we are currently inducing, we now need to grapple with the detail.

All this will come as no surprise to *Geoscientist* readers, because last year some members of the Stratigraphy Commission flagged Eocene and Toarcian climate analogues as a priority for policy makers. Perhaps it is time to consider the IETM as 'a striking example' that warrants more than a brief subsection within an IPCC assessment chapter?

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