PALAEOCLIMATE

Global warmth with little extra CO_2

Most climate models consider only short-term processes such as cloud and sea-ice formation when assessing Earth's sensitivity to greenhouse-gas forcing. Mounting evidence indicates that the response could be stronger if boundary conditions change drastically.

Birgit Schneider and Ralph Schneider

In the Early Pliocene, three to five million years ago, global temperatures were about 3–4° C warmer than today in the low latitudes, and up to 10° C warmer nearer the poles[1,2]. Climate simulations and reconstructions of this relatively recent period (geologically speaking) may help constrain realistic magnitudes of future warming[3]. Under commonly assumed greenhouse forcing scenarios, atmospheric carbon dioxide concentrations of 500–600 ppmv — roughly twice the preindustrial level — would be required to produce the climate of the Pliocene. Writing in *Nature Geoscience*, Pagani *et al.*[4] and Lunt *et al.*[5] suggest that much lower carbon dioxide concentrations in the atmosphere governed the Early Pliocene warm period, with potentially dire implications for the long-term future of the planet.

According to the consensus of scientists as presented in the fourth assessment report from the Intergovernmental Panel on Climate Change (IPCC), a doubling of atmospheric CO_2 concentrations compared with preindustrial levels would be expected to lead to a warming of global mean temperatures of about 3° C (Fig. 1). Termed climate sensitivity, the warming effect of doubling CO_2 levels summarizes short-term feedbacks between the atmosphere and upper ocean that typically reach an equilibrium state within years or decades, such as changes in atmospheric water vapour concentrations, snow albedo, sea-ice albedo, aerosols and clouds. The likely range of climate sensitivity between 2 and 4.5° C is derived from coupled atmosphere–ocean models that simulate only physical processes (and not, for example, vegetation changes)[3]. The range is also in broad agreement with proxy data of palaeoclimate[6,7] over glacial–interglacial cycles of the past 800,000 years — atmospheric CO_2 concentrations can be measured from air inclusions in Antarctic ice cores[8].

Pagani and colleagues[4] go further back in time, three to five million years ago. Temperatures at that time are reasonably well constrained by data, but in the absence of ice cores reaching back far enough in time, atmospheric CO_2 concentrations are difficult to determine. Pagani and colleagues present a reconstruction using the carbon isotopic composition of specific organic compounds called alkenones that are produced by a specific group of phytoplankton known as coccolithophorids or prymnesiophytes. These organisms dwell in the surface ocean and their remains are preserved in marine sediments. Studies on modern phytoplankton at sea and in culture experiments strongly suggest that the $^{13}C/^{12}C$ ratio of their organic tissue is controlled to large extent by surface ocean CO_2 concentration and growth rates. Applying this relationship to the fossil record gives estimated atmospheric CO_2 levels on the order of only 360–420 ppmv for the warm Early Pliocene period — much lower than expected from our best estimate of climate sensitivity.

The alkenone carbon isotope approach is known to have a number of caveats. For example, past changes in growth rates or nutrient supply as well as incomplete equilibration of partial CO_2 pressure between the atmosphere and surface ocean would introduce errors that could call for caution when inferring Pliocene atmospheric CO_2 levels. However, there is independent support for low levels. Another study, covering the past 20 million years, estimated Pliocene atmospheric CO_2 levels at no more than 325 ppmv (or at most 350 ppmv when data points just outside the Pliocene epoch

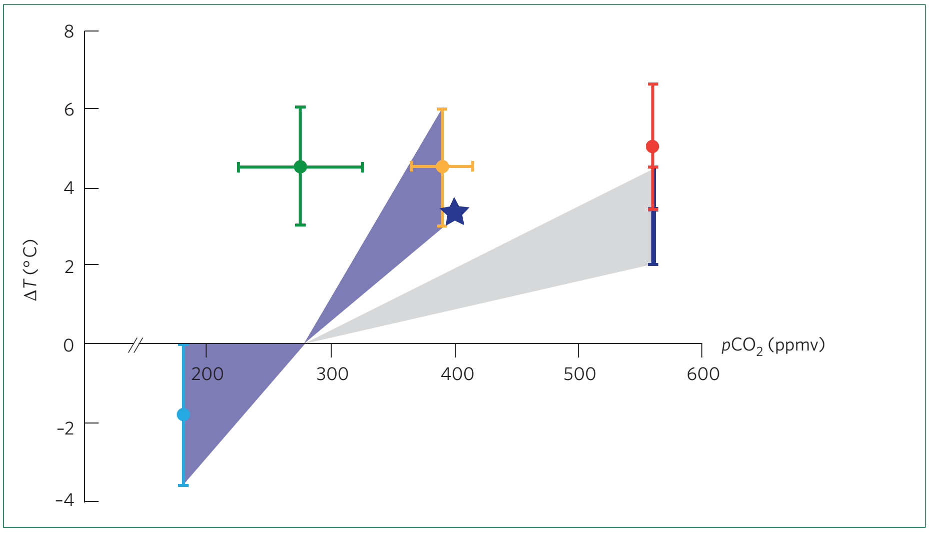

Figure 1 | Envelopes of temperature change (Δ*T*) compared with preindustrial temperatures for different atmospheric carbon dioxide concentrations. The reconstructions of the Pliocene by Pagani *et al.*[4] (yellow filled circle) and Lunt *et al.*[5] (blue star) agree that early Pliocene temperatures were around 4° C warmer than in preindustrial times, at atmospheric concentrations of around 400 ppmv, implying a much stronger climate sensitivity than estimates for future climate change (grey shaded area)[4]. Support for a higher sensitivity of Earth's temperatures to atmospheric carbon dioxide concentrations comes from reconstructions of tropical sea surface temperatures over the past three glacial–interglacial cycles (red filled circle)[6], and from another Pliocene reconstruction (green filled circle)[9]. Bars denote errors or ranges of estimates as given by the respective publications. Estimates of climate sensitivity during the cold time of the Last Glacial Maximum (blue filled circle)[7] are consistent with a wide range of sensitivities.

are considered), despite average surface temperatures that were 3–5° C higher than today[9]. These estimates are independent of the constraints found by Pagani and colleagues, because they are not based on alkenones. Instead they are based on the ratio of boron and calcium in calcitic shells of planktonic foraminifera — unicellular zooplankton that live in the surface ocean. The boron to calcium ratio of foraminiferal remains is assumed to also be regulated by the partial pressure of CO_2 in the atmosphere and therefore the surface ocean, and by the ambient temperature during the lifetime of the foraminifera.

Finally, in yet another independent approach, Lunt and colleagues[5] simulated the Early Pliocene climate using a coupled ocean–atmosphere model. They used proxy data for the slow-adjusting components of the Earth system, such as vegetation and ice sheets, from palaeoclimate reconstructions[10] to constrain the boundary conditions of the model. Separating the contributions of other factors such as orography and the effect of atmospheric CO_2 levels on surface temperatures at the time, the authors conclude that when calculating the long-term response of the climate system to rising greenhouse-gas concentrations in the atmosphere, the slow-adjusting contributions cannot be neglected. They estimate that the overall temperature response to a doubling of atmospheric CO_2 concentrations is 30–50% higher when feedbacks on longer timescales are taken into account. Lunt and colleagues term this more comprehensive measure the Earth system sensitivity, and conclude that CO_2 levels around 400 ppmv are entirely plausible for the Early Pliocene.

The possibility of such low CO_2 levels three to five million years ago was heatedly discussed at a workshop on Pliocene climate in Bordeaux, France at the end of October this year[11]. Taking together the emerging evidence with previous results, such as an early reconstruction based on the size of terrestrial plant leaf stomata[12], the consensus from the meeting converged on a best estimate for Pliocene atmospheric CO_2 concentrations of about 400 ppmv, with a possible error of 50 ppmv in either direction.

The conclusion of a high Earth system sensitivity[5,13] is particularly worrying if there is a potential for the hitherto slow components of the climate system to respond more quickly in the face of rapidly increasing CO_2 emissions. If today's continental ice-sheets vanish rapidly, or if terrestrial vegetation patterns change dramatically in a short period of time, the higher Earth system sensitivity of the Pliocene could be more relevant for future climate than the current notion of climate sensitivity.

The Pliocene differed from the present day in that it was characterized by significantly different continental vegetation patterns, and a much smaller extent of ice sheets and sea ice. It is worth taking note that in this earlier world, temperatures were 3–10° C higher than today at atmospheric CO_2 levels not far above present concentrations of about 385 ppmv.

It should be noted that the Pliocene model[5] does not include the full carbon cycle or the feedbacks that originate from biogeochemical processes in the ocean. These effects could be important as accelerators for a much faster climate response[14] and should be focused on in future modelling efforts. A number of proxy-based studies already indicate that Pliocene ocean-nutrient conditions and biological productivity were significantly different from today[15,16], with probably important implications for the carbon cycle at work during the Pliocene.

Following on from the studies by Pagani and Lunt and their colleagues[4,5], the Pliocene is likely to be an important benchmark in our attempt to find analogues for future climate change. ❐

Birgit Schneider and Ralph Schneider are at the Institute of Geoscience and Excellence Cluster ´Future Ocean´, Christian-Albrechts University, 24118 Kiel, Germany.
e-mail: bschneider@gpi.uni-kiel.de; rschneider@gpi.uni-kiel.de

References

1. Dowsett, H. J., Chandler, M. A. & Robinson, M. M. *Phil. Trans. R. Soc. A* **367,** 69–84 (2009).
2. Dekens, P. S., Ravelo, A. C. & McCarthy, M. D. *Paleoceanography* **22,** 1–12 (2007).
3. IPCC *Climate Change 2007: Synthesis Report* (eds Pachauri, R. K. & Reisinger, A.) (Cambridge Univ. Press, 2007).
4. Pagani, M., Liu, Z., LaRiviere, J. & Ravelo, A. C. *Nature Geosci.* doi:10.1038/ngeo724 (2009).
5. Lunt, D. A. *et al. Nature Geosci.* doi:10.1038/ngeo706 (2009).
6. Lea, D. *J. Clim.* **17,** 2170–2179 (2004).
7. MARGO Project Members *Nature Geosci.* **2,** 128–132 (2009).
8. Lüthi, D. *et al. Nature* **453,** 379–382 (2008).
9. Tripati, A. K., Roberts, C. D. & Eagle, R. A. *Science* **326,** 1394–1397 (2009).
10. Pliocene Research, Interpretation and Synoptic Mapping (PRISM) <http://geology.er.usgs.gov/eespteam/prism> (2009).
11. http://www.plioclimworkshop.com
12. Kürschner, W. M., van der Burgh, J., Visscher, H. & Dilcher, D. L. *Mar. Micropaleontol.* **27,** 299–312 (1996).
13. Knutti, R. & Hegerl, G. C. *Nature Geosci.* **1,** 735–743 (2008).
14. Friedlingstein, P. *et al. J. Clim.* **19,** 3337–3353 (2006).
15. Sigman, D. M., Jaccard, S. L. & Haug, G. H. *Nature* **428,** 59–63 (2004).
16. Etourneau, J., Martinez, P., Blanz, T. & Schneider, R. R. *Geology* **37,** 871–874 (2009).

Published online: 20 December 2009