to analyse their behaviour during abrupt changes. If the models are to be used for the prediction of potential future events of abrupt change, their ability to simulate such events needs to be firmly established — science is about evidence, not belief systems.

At present, computational expense prevents state-of-the-art, IPCC-type models from being run for the longer time periods that are essential for investigating past climate events. Improved methods for identifying critical thresholds in models[16] may help. Furthermore, a scientifically more seamless understanding of the effects of resolution is necessary to evaluate simulations at lower resolution that are faster and hence allow longer runs and more thorough testing of different possible model set-ups.

In the meantime, we need to be cautious. If anything, the models are underestimating change, compared with the geological record. According to the evidence from the past, the Earth's climate is sensitive to small changes, whereas the climate models seem to require a much bigger disturbance to produce abrupt change. Simulations of the coming century with the current generation of complex models may be giving us a false sense of security. ❐

Paul Valdes is in the School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK.
e-mail: P.J.Valdes@bristol.ac.uk

References

1. Russill, C. & Nyssa, Z. *Glob. Environ. Change* **19,** 336–344 (2009).
2. Lenton, T. M. *et al. Proc. Natl Acad. Sci. USA* **105,** 1786–1793 (2008).
3. Kriegler, E., Hall, J. W., Held, H., Dawson, R. & Schellnhuber, H. J *Proc. Natl Acad. Sci. USA* **106,** 5041–5046 (2009).
4. Thompson, J. M. T. & Sieber, J. *Int. J. Bifurc. Chaos* **21,** 399–423 (2011).
5. Zachos, J. C., Dickens, G. R. & Zeebe, R. E. *Nature* **451,** 279–283 (2008).
6. Spicer, R. A. *et al. Earth Planet. Sci. Lett.* **267,** 228–235 (2008).
7. Braconnot, P. *et al. Clim. Past.* **3,** 261–277 (2007).
8. Ganopolski, A. & Rahmstorf, S. *Nature* **409,** 153–158 (2001).
9. Hemming, S. R. *Rev. Geophys.* **42,** RG1005 (2004).
10. Kageyama, M., Paul, A., Roche, D. M. & Van Meerbeeck, C. J. *Quat. Sci. Rev.* **29,** 2931–2956 (2010).
11. McManus, J. F., Francois, R., Gherardi, J. M., Keigwin, L. D. & Brown-Leger, S. *Nature* **428,** 834–837 (2004).
12. Hofmann, M. & Rahmstorf, S. *Proc. Natl Acad. Sci. USA* **106,** 20584–20589 (2009).
13. Liu, Z. *et al. Science* **325,** 310–314 (2009).
14. Wunsch, C. *Quat. Sci. Rev.* **29,** 1960–1967 (2010).
15. Stanford, J. D. *et al. Quat. Sci. Rev.* **30,** 1047–1066 (2011).
16. Huisman, S. E., den Toom, M., Dijkstra, H. A. & Drijfhout, S. *J. Phys. Oceanogr.* **40,** 551–567 (2010).
17. Winguth, A., Shellito, C., Shields, C. & Winguth, C. *J. Clim.* **23,** 2562–2584 (2010).

Where are you heading Earth?

Richard E. Zeebe

Accurate prediction of Earth's future warming hinges on our understanding of climate sensitivity. Palaeoclimatology will help solve the problem if the feedbacks included in palaeoclimate sensitivity are properly identified and reconstructions of past atmospheric CO_2 can be improved.

Perhaps the most burning question that we, as a climate community, need to address swiftly is: what will Earth's surface temperature be during the next few centuries if we continue to burn fossil fuels as we do now? Humanity might thrive under a slight temperature rise of 1 °C or so, or could be heading for more than 5 °C global warming, which by some standards may bear resemblance to the burning of Rome in the 1950s movie *Quo vadis* (Latin for 'Where are you going?'). In other words, we need to know accurately what the change in Earth's global surface temperature is per doubling of atmospheric CO_2, a measure often loosely referred to as climate sensitivity. Remarkably, rather than looking to the future, the answer might come from looking to the past (*unde venis*, 'where do you come from?').

By studying the relationship between greenhouse gas forcings and global temperature changes during past climate episodes, palaeoclimatology currently has a unique opportunity to fundamentally contribute to understanding climate sensitivity. At present, one of the standard tools for estimating climate sensitivity is the use of numerical climate models. Unfortunately, model-derived climate sensitivities are subject to large uncertainties. This is not because climate models are flawed but simply because the climate system is complex and accurate predictions are inherently difficult. Studying past climates to estimate climate sensitivity inarguably has one great advantage over theoretical computer models: it is based on actual data. Unfortunately, palaeodata-derived climate sensitivities have large uncertainties as well. Errors can arise from issues such as dating, alteration of the climate signal after deposition, insufficient spatial and/or temporal coverage, and various uncertainties associated with the proxies for environmental variables such as temperature and past atmospheric CO_2 concentrations.

The most reliable archives of past changes in atmospheric CO_2 concentrations are ice-core records of the late Pleistocene glacial–interglacial cycles. However, ice-core CO_2 records exist for only the past 1 million years or so and cover climate periods that were mostly colder than the pre-industrial era and were associated with atmospheric CO_2 concentrations between about 180 and 280 ppmv. In contrast, we are heading for a warmer future — atmospheric CO_2 concentrations are already higher than 390 ppmv at present and will probably reach 700 ppmv by the end of this century. To study warm periods in Earth's history with $p\mathrm{CO}_2$ levels similar or higher than today's, we need to go back at least a few million years. No ice-core records reach this far back and we have to rely on other archives, primarily deep-sea sediment cores recovered by the various ocean drilling programmes.

In fact, most of what we know today about the climate of the past few hundred million years is based on deep-sea archives. Given this vital role of ocean drilling in climate science, it is incomprehensible that the US National Science Foundation has just announced a reduction in the 2012 schedule of the drilling vessel *JOIDES Resolution*, owing to budget priorities. Such decisions compromise the future of ocean drilling, including its indispensable contribution to understanding Earth's climate system.

Climate sensitivity is often referred to as the equilibrium change in global mean surface temperature following a doubling of atmospheric CO_2. The concept seems elementary but the catch here is the definition of 'equilibrium', which depends on the timescale considered. This has led to much confusion in the literature. For example, continental ice sheets respond slowly to changes in radiative forcing and their feedback on temperature may be ignored in the model-derived equilibrium climate sensitivity on a centennial timescale. However, the very same feedback is naturally part of the equilibrium climate sensitivity derived from palaeoclimate records in cases where the temporal data coverage extends beyond the characteristic response time of ice sheets. In this example, the climate sensitivities derived from models and from palaeodata are obviously not the same and comparing the two is like comparing apples and oranges.

To distinguish between different types of climate sensitivity, terms such as 'fast-feedback sensitivity' and 'Earth system sensitivity' have been coined[1,2]. Estimates of climate sensitivity that include only fast feedbacks such as changes in water vapour, clouds, snow, and sea ice are typically 2.0–4.5 °C per doubling of CO_2 (ref. 3). In contrast, for some warm periods in Earth's history such as the Pliocene epoch (about 5.3 to 2.6 million years ago), climate sensitivity has been estimated at 7–10 °C per doubling of CO_2 based on palaeoclimate data[4]. The latter estimate, however, includes Earth system feedbacks on all timescales such as changes in non-CO_2 greenhouse gases, vegetation, dust/aerosols, ice sheets, ocean circulation, marine productivity, weathering and more. It is therefore crucial for researchers to properly define what they mean by climate sensitivity and to spell out the pertinent timescales and feedbacks involved. A workshop was held in March 2011 in Amsterdam to address the issue and a manuscript is in preparation that will provide guidance on how to aptly deal with climate sensitivity in palaeoclimate studies.

The Pliocene is often presented as a useful analogue for the future because atmospheric CO_2 was higher than pre-industrial values (~400 versus 280 ppmv), whereas the continental configuration was essentially identical to today's. However, the Pliocene is also somewhat limited as a future analogue for at least two reasons. First, CO_2 values of 400 ppmv are relatively moderate compared with 700 ppmv as expected by the end of this century. Second, the Pliocene, as well as many other geologic periods, represents a long-term steady state of the Earth system that was established slowly, on timescales of millions of years. On the contrary, today's human-induced disruption represents a massive and rapid perturbation of the Earth system on timescales of only centuries. To find a perturbation analogue in the geologic record that was associated with a large and rapid carbon input, we may have to go back 55 million years to the Palaeocene–Eocene Thermal Maximum (PETM).

During the PETM a large mass of carbon was released into Earth's surface reservoirs[5], and surface temperatures rose by 5–9 °C in a few thousand years. My colleagues and I recently estimated the size of the PETM carbon input based on sediment records of deep-sea carbonate dissolution and showed that the subsequent rise in atmospheric CO_2 alone was insufficient to explain the full amplitude of global warming[6]. We concluded that in addition to direct CO_2 forcing, other processes must have caused a portion of the PETM warming. The so-called climate sceptics subsequently abused our study as evidence that CO_2 would have no control on climate. Such statements are ignorant at best, more likely deliberately misleading. Our study showed that there were processes in addition to CO_2 forcing that caused part of the warming, not that CO_2 was irrelevant. The processes are as yet unidentified — some may have operated independently[5,7], others as a response or feedback to the CO_2 release. Regardless, these processes demand our attention because they could be critical for accurate future warming predictions.

The PETM probably remains the most valuable case study for a massive and rapid carbon release throughout the Cenozoic era. Aberrations such as the PETM are key to understanding climate sensitivity during transient events, which serve as perturbation analogues for the present carbon release from human activities. However, what is needed at this stage is no more inflated numbers for the carbon release that violate observational constraints, but a realistic assessment of the geochemical evidence. So far, deep-sea sediment cores consistently show minor carbonate dissolution in the deep Pacific Ocean during the PETM, as recently confirmed by another core from the equatorial Pacific[8]. These observations provide firm constraints on the magnitude and location of the carbon input[6,9] and have to be taken into account before excessive numbers are shouted from the rooftops.

Ideal, of course, would be reconstructions of changes in past atmospheric CO_2 concentrations based on direct proxy records to constrain carbon input and climate sensitivity — not only during the PETM but also during other climate episodes of the past. Although progress has recently been made to improve existing proxies for past atmospheric CO_2 concentrations and seawater carbonate chemistry parameters[10], the uncertainties are still significant, particularly in the more distant past. At present, it seems that key to improving the accuracy of palaeoclimate-sensitivity estimates is to both refine existing pCO_2 proxies and encourage creative minds to develop new pCO_2 proxies.

In 1887, Oscar II, King of Sweden, established a prize for anyone who could find the solution to a problem in classical mechanics in which n mass points interact gravitationally according to Newton's laws, known as the n-body problem. The prize was awarded to the French mathematician and physicist Henri Poincaré for his groundbreaking contribution to the competition. Poincaré did not completely solve the problem, but his work initiated a new era in celestial mechanics and laid the foundation for the chaos theory. I suggest establishing a prize in climate science, sponsors willing, for anyone who can find a reliable and accurate proxy for past atmospheric CO_2 concentrations that works over timescales from millennia to hundreds of millions of years. Given what is at stake, namely reconstructing Earth's climate history and accurately predicting Earth's future warming (*Quo vadis, unde venis, Terra?*), it's certainly worth a try. ❐

Richard E. Zeebe is in the School of Ocean and Earth Science and Technology, Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA.
e-mail: zeebe@soest.hawaii.edu

References

1. Hansen, J. *et al. Open Atmos. Sci. J.* **2,** 217–231 (2008).
2. Lunt, D. J. *et al. Nature Geosci.* **3,** 60–64 (2010).
3. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
4. Pagani, M., Liu, Z., LaRiviera, J. & Ravelo, A. C. *Nature Geosci.* **3,** 27–30 (2010).
5. Dickens, G. R. *Clim. Past Discuss.* **7,** 1139–1174 (2011).
6. Zeebe, R. E., Zachos, J. C. & Dickens, G. R. *Nature Geosci.* **2,** 576–580 (2009).
7. Sluijs, A. *et al. Nature* **450,** 1218–1221 (2007).
8. Leon-Rodriguez, L.& Dickens, G. R. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **298,** 409–420 (2010).
9. Carozza, D. A., Mysak, L. A. & Schmidt, G. A. *Geophys. Res. Lett.* **38,** L05702 (2011).
10. Beerling, D. J. & Royer, D. L. *Nature Geosci.* **4,** 418–420 (2011).