commentary

Built for stability

Paul Valdes

State-of-the-art climate models are largely untested against actual occurrences of abrupt change. It is a huge leap of faith to assume that simulations of the coming century with these models will provide reliable warning of sudden, catastrophic events.

Critical thresholds may be inherent to the climate system. If so, they could lead to abrupt, and perhaps irreversible, changes to the Earth system. This possibility has caught the imagination of the public — often under the emotive term 'tipping points' — and has led to a huge growth in media and scientific publications on the topic in the past few years[1]. If we are about to cross such a critical threshold, the implications for climate adaptation strategies could be significant. Likewise, knowledge of thresholds would have a strong influence on mitigation policy, not least by helping to define the meaning of the term 'dangerous climate change'.

Yet it is less clear exactly how such critical thresholds should be defined[2], whether they even exist and, if so, whether we are close to one. Expert elicitation[3] is subjective. And attempts to identify early signals of catastrophic change with a variety of nonlinear system techniques[4] are, in practice, unlikely to provide warning with sufficient lead times. Climate model simulations are the only other means for gaining advance knowledge of sudden climate change. It is therefore crucial to assess whether the available models are capable of investigating these phenomena.

I argue that climate models of the current generation, as used in the latest assessment of the Intergovernmental Panel on Climate Change (IPCC), have not proved their ability to simulate abrupt change when a critical threshold is crossed. I discuss four well-documented examples of past rapid climate change (Box 1). In two cases, the models did not adequately capture the basic climate configuration before abrupt change ensued, and in the remaining two examples, to initiate abrupt change the models needed external nudging that is up to ten times stronger than reconstructed. The models seem to be too stable.

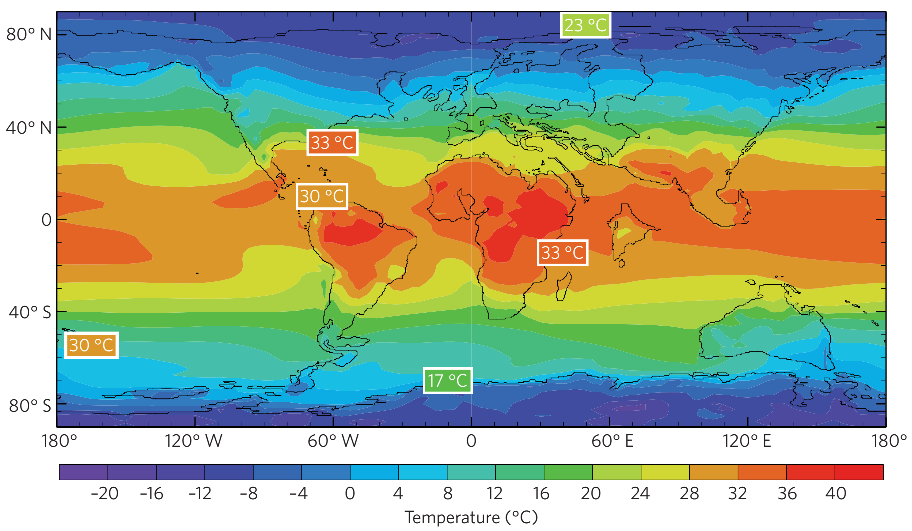

Figure 1 | Simulated and reconstructed early Eocene temperatures. Typical model predictions of the mean annual surface temperature for the early Eocene (background colours) broadly agrees with reconstructions from a variety of proxy palaeoclimate temperature estimates[17] (labels) at tropical latitudes. At high latitudes, however, the differences between the model and palaeodata can exceed 20 °C.

Past abrupt change

Although it is difficult to unambiguously identify true critical thresholds in the palaeorecord, there are well-documented examples of climate transitions that are abrupt in the sense that the climate response is more rapid than the forcing. Some of these events, such as the four examples discussed below, could have a direct bearing on climate predictions for the twenty-first century.

During the Palaeocene–Eocene Thermal Maximum[5], about 55.8 million years (Myr) ago, a rapid warming event was accompanied by a significant perturbation to the carbon cycle. Temperature rose by 5 °C in the tropics and by up to 20 °C at high latitudes, within a few thousand years. The most popular explanation suggests that a massive release of methane from submarine hydrates led to an injection of carbon into the atmosphere that is comparable in magnitude to that estimated for the current century. The event therefore has considerable contemporary interest. However, modelling of the period has a fundamental problem. Geological data suggest that the background climate state of the late Palaeocene and early Eocene was characterized by an extremely flat temperature gradient between the Equator and the poles. And according to the reconstructions, temperatures in the continental interiors rarely dropped below 0 °C, even in winter.

Climate models have been unable to simulate the extent of this warmth in the high latitudes (Fig. 1). Not being able to start from a realistic global temperature distribution for the late Palaeocene makes it unrealistic to simulate the further abrupt warming associated with the Palaeocene–Eocene Thermal Maximum. More worryingly, similarly flat latitudinal temperature gradients are a common feature of extreme warm climates of the past[6], suggesting that IPCC-type, complex climate models may not be well suited to simulating climate dynamics during these past, extremely warm periods. Whether the planet's climatic conditions projected for the end of this century can be considered 'extremely warm' remains an unanswered question.

The rapid desertification of northern Africa about 5,500 yr ago represents a geologically much more recent incident of abrupt change. In the early and mid-Holocene epoch, between about 9,000 and 5,500 yr ago, it was seasonally warmer than today and the region now occupied by the Sahara was much wetter and vegetated (sometimes referred to as the 'green Sahara'). The transition to the dry Sahara of today occurred relatively rapidly, over decades to centuries. Again, the potential relevance to the next century is evident — and again, full-complexity climate models, such as those typically used in the IPCC assessments, do not adequately simulate the climatic conditions before the abrupt change occurred. Specifically, the simulations do not produce the full extent of the greening of northern Africa during the early and mid-Holocene[7]. But if the simulated mid-Holocene Sahara is not vegetated in the first place, there is no hope of simulating its rapid desertification around 5,500 yr ago.

A third example is the collapse of the Atlantic meridional overturning circulation, a scenario that has attracted much attention in the scientific literature and media alike. Based on palaeodata, the overturning circulation is believed to have collapsed during six abrupt cooling events of the past 120,000 yr, termed Heinrich events. The circulation changes resulted in an extremely rapid drop in Northern Hemisphere temperatures, with regional changes of up to 10 °C. According to the conventional explanation, large amounts of fresh water from the northern ice sheets entered the North Atlantic and caused a collapse of the overturning circulation. The possibility of such a change in the future, potentially in response to glacial meltwater or more precipitation in the northern North Atlantic, has been one of the most widely discussed possibilities for a critical threshold.

Relatively simple conceptual models and models of intermediate complexity have had some considerable success in simulating Heinrich events, and exhibit complex behaviour with numerous equilibria, hysteresis and abrupt changes. The latter models also suggest that the sensitivity of the climate system is higher during glacial times[8]. Yet for full-complexity models of the type used in the IPCC reports, the results are different. In the classic simulation, a large flux of fresh water, usually about one sverdrup (Sv, equivalent to 1 million $m^3 s^{-1}$), is inserted into the North Atlantic Ocean under present-day climate conditions, to mimic a large amount of meltwater. This pulse of fresh water causes a collapse in the simulated Atlantic meridional overturning circulation and parallels are then made to Heinrich events.

However, the input of fresh water during the real Heinrich events are now consistently estimated at only 0.1 or 0.2 Sv, about a tenth of the value used in simulations[9]. In turn, simulations with a more realistic freshwater flux — even if initiated in the more sensitive, glacial climate state — generally result in a much weaker response[10]: a relatively modest circulation decline by about 30%, changes in Greenland's air temperature of only 2–3 °C and a recovery within a couple of centuries, instead of the few decades suggested by palaeodata[11]. Indeed, multiple equilibria and hysteresis have rarely been seen in full-complexity models, and have consequently been suggested to be artefacts of simpler models. Overall, full-complexity models are either nowhere near as sensitive as the real climate system[12], or they have never been tested properly.

Finally, about 25 rapid warming events have been recorded in the past 120,000 yr, starting from a cold, glacial climate state. These events are part of the Dansgaard–Oeschger climate cycles, and are characterized in the Greenland ice core record by very rapid rises in air temperature of up to 8 °C within a few decades. At the same time, the ice cores record large changes to atmospheric methane concentrations, which indicate that the events had a climate impact well beyond Greenland. Yet in terms of simulations with complex climate models, the warming events linked to Dansgaard–Oeschger cycles are even more problematic than the Heinrich events, partly because the mechanisms causing them are still poorly understood. For example, to simulate the rapid warming about 14,700 yr BP, the last one of these events, an injection of meltwater lasting many thousands of years longer than reconstructed from evidence was required[13].

Box 1 | Four examples of past abrupt change.

The Palaeocene–Eocene Thermal Maximum. A rapid warming event about 55.8 Myr ago started with warm climate conditions with a smaller difference between temperatures at the Equator and the high latitudes. Complex climate models do not adequately simulate the warm climate before the abrupt change set in.

The desertification of northern Africa. Between about 9,000 and 5,500 yr ago, the region that is now the Sahara was much wetter and supported a steppe-type vegetation. The transition to the current desert state occurred in decades to centuries. Complex climate models fail to simulate the vegetated state, and can not therefore capture this event of rapid change.

Collapse of the Atlantic meridional overturning circulation. During the glacial period between about 120,000 and 12,000 yr ago, the meriodional overturning circulation in the Atlantic Ocean collapsed during six Heinrich events, most probably in response to fresh water entering the North Atlantic. Complex climate models simulate such a shut-down — but only in response to a freshwater injection as much as ten times the magnitudes estimated for the past.

Dansgaard–Oeschger rapid warming events. Between Heinrich events, 25 incidences of rapid warming, by up to 8 °C within a few decades in Greenland, are consistently recorded in the ice cores. We don't even fully understand the mechanisms for such changes and simulating the final one of these events required an injection of fresh water into the ocean that was large and many thousand years longer than is thought realistic.

Try and test them

Overall, the modelling of past abrupt events does not give us confidence in the ability of complex models to simulate critical threshold behaviour that we know has occurred in the past. In response to this deficiency, first we need to challenge the palaeodata[14], and continue to improve our knowledge of past forcing factors and the ensuing climate response. Second, we need to understand the physics and dynamics of documented abrupt change events better[15]. And third, we need to develop more sophisticated tests of the full complexity models — tests that help 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. ❒

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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).

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Where are you heading Earth?

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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$$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.