Earth system models - How well do Earth system models simulate the dynamics of global change?

PRESENT PAST

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How well can Earth system models simulate the dynamics of global change? Well, if we wait long enough, we'll find out. But by then the models being judged will be deemed out-of-date and the latest models will be argued to be far superior! Recently models have under-predicted the rate of global warming and sea-level rise (Rahmstorf et al. 2007), and have failed to forecast the abruptness of Arctic sea-ice retreat (Stroeve et al. 2007) or the start of ocean de-oxygenation. This does not bode well.

When the dynamics of global change are basically linear – that is, the response is proportional to some forcing – and the forcing and response are accurately captured, the models should do a good job. Global warming in response to radiative forcing would be a great example, if only the radiative forcing effects of aerosols and the climate sensitivity to a given radiative forcing were not both highly uncertain (see pages 10/11 and 20/21 of this issue). The best way to reduce this uncertainty is to continue to reduce aerosol forcing and wait to see the climate response.

The prediction problem gets more difficult when the dynamics of change could be highly non-linear. Current global models struggle to capture potential climate “tipping points” at sub-continental scales (Fig. 1) (Lenton et al. 2008). For example, observations support the theory that the Atlantic meridional overturning circulation is “bi-stable” with an alternative collapsed state stable under the present climate, which it could conceivably be tipped into (Drijfhout et al. 2011). Yet the last generation of models were systematically biased, with just one stable ocean circulation state (Drijfhout et al. 2011), so it is no surprise that they did not forecast the possibility of future collapse (IPCC 2007).

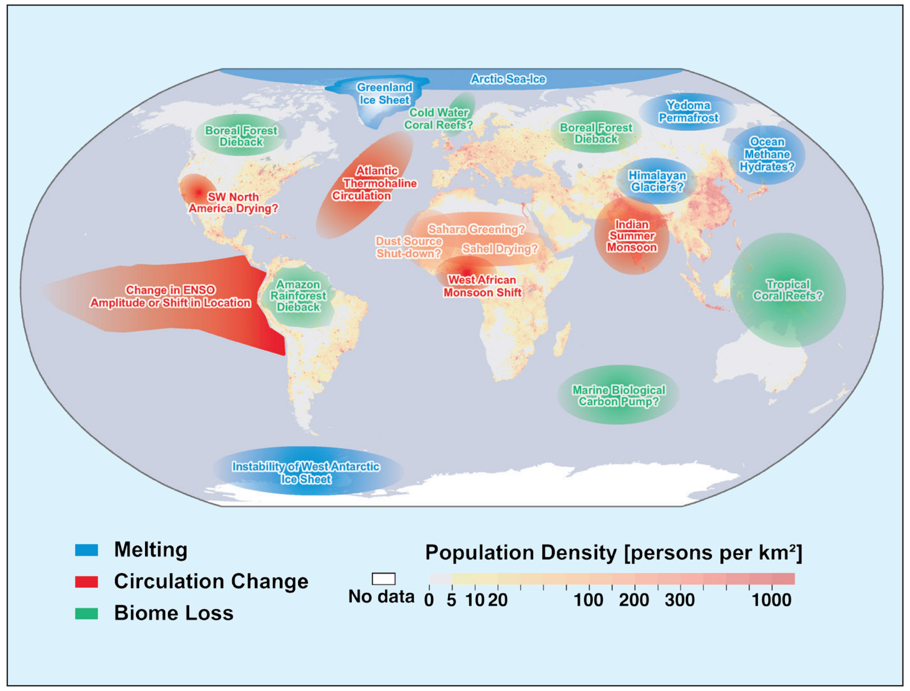

Figure 1: Map of potential policy-relevant tipping elements in the climate system, categorized into those involving ice melting, circulation changes, or biome losses – updated from Lenton et al. (2008) by Veronika Huber, Martin Wodinski, Tim Lenton and Hans-Joachim Schellnhuber.

Sometimes key processes or systems are simply missing from the models. Collective inability to put a number on the future contribution of ice sheets to sea-level rise (IPCC 2007) has provoked a welcome revolution in the modeling of ice-sheet dynamics. But we must be wary of the “kitchen sink” tendency to keep putting more and more into Earth system models. Increasing complexity has been sold on the argument that it will reduce uncertainty in future projections, but it was never going to do that. Uncertainty has predictably increased as more forcing agents, couplings and feedbacks have been added to the models.

Century-scale runs with multiple simultaneous forcing agents and feedbacks are important for policymakers, but not the most scientifically informative if one wants to isolate the effects of a particular forcing or feedback, or attribute the causes of a particular change. What we need is a new way of using models together with available data to bridge the widening gap between predictive modeling and mechanistic understanding. The ocean overturning example highlights the need to recalibrate models using available data to get their stability properties right. But this is not just an initial condition problem; it will involve altering the parameters and even the processes in the models.

Earth system models are still at heart climate models with bits added on. This is of course sensible if – as many of us believe – climate change is the most dangerous global change that we as a species are driving. But it is worth considering the possibility that another global change might turn out to be more important. If, for example, our rampant mining of phosphates and fixing of nitrogen could ultimately trigger a global oceanic anoxic event, do we have a well-posed tool to assess this? Century-scale climate models are clearly inappropriate. Intermediate complexity models may be better posed. But I still see a need for truly “Earth system” models that can help define all of our planetary boundaries (Rockström et al. 2009).

Selected references

Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2012_1.pdf

Drijfhout S, Weber S and van der Swaluw E (2011) *Climate Dynamics* 37: 1575-1586

Lenton TM et al. (2008) *PNAS* 105: 1786-1793

Rahmstorf S et al. (2007) *Science* 316: 709

Rockström J et al. (2009) *Nature* 461: 472-475

Stroeve J et al. (2007) *Geophysical Research Letters* 34, doi: 10.1029/2007GL029703

Climate models, in particular the “big” general circulation models used for climate prediction, are first evaluated in comparison to present climate. This step is crucial, but does not warrant a correct sensitivity to external forcings or a realistic representation of the speed of climatic changes under time-dependent forcings. As underlined by Tim Lenton (this issue), it is unreasonable to just wait and see if the climate changes predicted by the current models have actually happened. But we can turn to the past and to the numerous paleo-records.

What do they tell us? That it is impossible to find a close analogue to the recent and probably future climate change in the paleo-record, in terms of forcing and in terms of the speed at which it occurs. But there *are* periods warmer than present and there *are* periods of abrupt climate changes. These past scenarios provide an endless list of challenges for climate – and more generally Earth System – modelers. The challenges fall into three categories. Are we able to model (and thus prove we understand) (1) the direction, (2) the amplitude and (3) the speed of the reconstructed climate changes?

For a long time, general circulation models have only been used to tackle the first two tasks, by considering simulations at equilibrium with external forcings and boundary conditions different from today. The Palaeoclimate Modelling Intercomparison Project (Braconnot et al. 2007) has led such comparisons for the Mid-Holocene (MH) and the Last Glacial Maximum (LGM). Very often, the models have proved to be able to simulate the sign of the reconstructed climate differences, but not their amplitude, e.g. in African monsoon amplification during the Holocene or for the European or Greenland cooling during the LGM. Does this prove the models have a too low sensitivity? Maybe, and there are many processes (e.g. vegetation, ice-sheets) that models do not account for yet. Their inclusion could increase model sensitivity to external forcing, at least regionally. On the other hand, we have to remember that the paleo-climatic reconstructions are also based on assumptions and associated with uncertainties. Direct (“forward”) modeling of the paleo-climate indicators such as vegetation, oxygen isotopes or abundance of foraminifera offers a solution by accounting for multiple factors controlling the environmental indicators. Forward modeling has shown that formerly neglected processes needed to be considered in the interpretation of a record and that this can result in more satisfactory model-data comparisons than those between modeled and reconstructed climate variables (e.g. LeGrande et al. 2006).

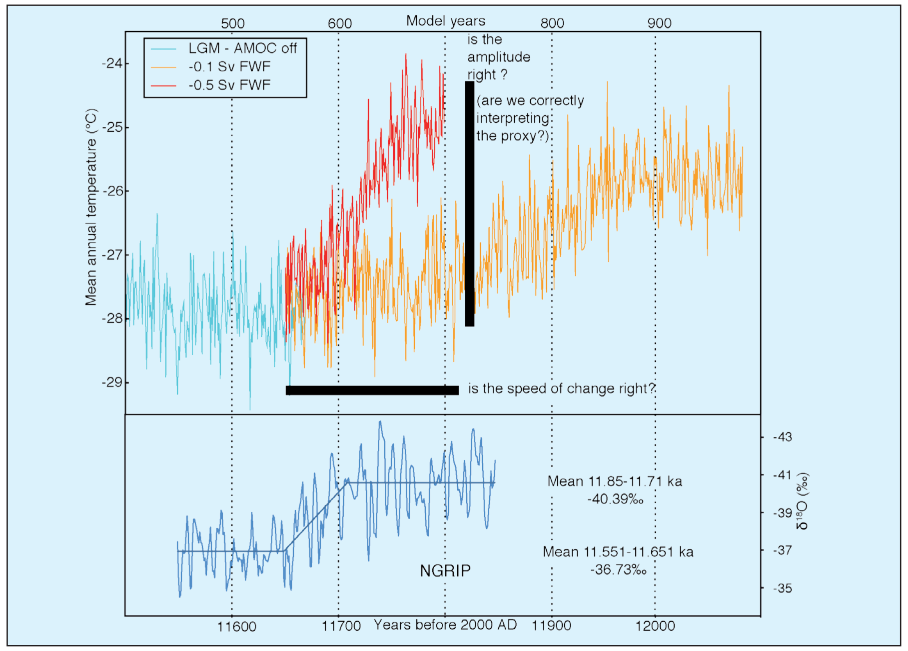

*Figure 1: Qualitative comparison of modeled warming events (**upper panel**) with a real event as recorded in the NGRIP ice core in Greenland between 11.6 and 11.8 ka BP (**lower panel**; Steffensen et al. 2009). The model results are for simulations using Last Glacial Maximum forcings. (blue) reference run, Atlantic Meridional Overturning Circulation (AMOC) "turned off", (orange) with a North Atlantic fresh water forcing of -0.1 Sv and (red) of -0.5 Sv (1 Sv = 10^6 m^3 s^{-1}).*

This is only a first step. As questions on the speed of future climate change and our ability to adapt to them arise, we can return to the paleo-record. On which timescales can climatic change occur? Our knowledge on this topic has greatly increased since a few decades ago, when climate history was considered to occur on tectonic and Milankovitch (ice age) timescales only. The discovery of abrupt climate changes in Greenland and elsewhere during the last glacial cycle has raised the challenge to understand changes that occurred over a few decades or even just a few years (Steffensen et al. 2009), much shorter than the time-scale at which the external forcings evolved (Fig. 1).

These short time-scales imply that “big” models can now be used to test our understanding of these fast climate changes, in addition to Earth System Models of Intermediate Complexity (EMICS). EMICS have the advantage of running fast and include representations of the slow components of the climate system. As such, they have been used extensively to study climate evolution, but the origin of the abrupt Dansgaard-Oeschger warmings is still elusive. So far, no model, neither EMIC nor GCM, has been able to simulate such transitions without imposing ad-hoc fresh water flux forcings. Are our models too simple? Are there missing processes in our understanding? Do we overinterpret the proxies? Are the very fast climatic shifts recorded in Greenland the result of a large change in interannual variability superimposed on a slower climate evolution? On this topic, big models, equipped with “proxy simulators” might bring new enlightening perspectives.

References

Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2012_1.pdf

Braconnot et al. (2007) *Climate of the Past* 3: 261-277

LeGrande et al. (2006) *PNAS* 103: 837-842

Steffensen et al. (2009) *Science* 321: 680-684