FORUM

The Unknown and the Uncertain in Earth System Modeling

With the planet heating up, the urgent need to reduce uncertainty in climate projections could have consequences in the way Earth system models evolve. I argue that a period of confusion in the development of models can be beneficial and can lead to improved understanding and reduced uncertainty in due time. I have identified three phases of development in modeling—the illusion, the chaos, and the relief—through which models seem to evolve before their results can be said to approach the truth with some confidence.

Whereas these phases are based only on my limited observation of the field, they underline the fact that answers to scientific questions are usually 'unknown' before they become 'uncertain.' Realizing in which phase a model component may be could facilitate their development. I give examples from carbon cycle modeling and highlight the benefits of encouraging new and audacious approaches in modeling.

The illusion phase happens at the early stages of model development. It suffers from the lack of observations with which to evaluate model results, and from the implicit rule in peer review that published results are true until they are proved wrong. Thus, the first few published results initially take the place of the truth. The peer-review system leads to a situation in which models tend to reproduce published estimates with small incremental changes only; as publications around a topic accumulate, it becomes far easier to confirm published results than to prove them wrong. This is what Thomas Kuhn called "normal science" in his analysis of the structure of scientific revolutions [*Kuhn,* 1962]. To exit this phase, solid and challenging observations are needed.

Ocean carbon models are in the illusion phase. The first models that estimated the impact of climate change on the ocean carbon dioxide (CO_2) sink showed only a small response, and all models published since then have repeated these results [*Prentice et al.,* 2001]. Although these results may be correct because the physical dynamics has been constrained in part by observations [*Doney et al.,* 2004], the biological efficiency remains unexplored and is represented in a very similar way in all the published models, where the biological changes are dominated by changes in the physical supply of nutrients and not by the ecosystem response to climate change.

New observations on the variability of oxygen from both atmospheric [*Manning and Keeling,* 2006] and oceanic [*Garcia et al.,* 2005] measurements are presently challenging the biological component of oceanic carbon models, and will hopefully lead to a step into the chaos phase.

The chaos phase is the most creative and beneficial period in the development of models. Often because of conflicting evidence between models and observations, the modelers are not inhibited by pressure to confirm a published answer. Modelers are, on the contrary, driven by the possibility of exploring new dimensions, unconstrained even by observations. This phase may also trigger experimental or observational developments to understand the underlying processes, although data and model developments may appear to occur in parallel. Models tend to go their own way, leading to some incoherence between model results and the state of knowledge.

Terrestrial carbon models are in the chaos phase. Model results have no reference and are contradicting each other, with some models predicting an outgassing of CO_2 from the terrestrial biosphere in half a century and others showing persistent CO_2 sinks well into the future [*Friedlingstein et al.,* 2006]. Meanwhile, a myriad of experiments are trying to decipher the decomposition of soils under warming conditions [*Knorr et al.,* 2005], the competition of ecosystems [*Foley et al.,* 2003], and the productivity under changing cloud conditions [*Gu et al.,* 2003], just to cite a few examples. Research appears random and uncoordinated. To exit this phase, conceptual innovations are needed.

The relief phase comes when the basic concepts have been understood and included in models, and when reliable observations can be used to eliminate outlier model results. When this phase is reached, it is possible to reduce the uncertainty from a range of model results simply by doing more measurements or by fine tuning the processes or increasing the resolution in existing models.

In some respect, one could argue that climate models have reached the relief phase. They found creative ways to constrain climate change, for example, by looking at the model responses following volcanic eruptions [*Gleckler et al.,* 2006], the contrasting temperature increase between the day and night, or the probability distribution of the occurrence of extreme events [*Kiktev et al.,* 2003]. The evolution of these models is made in a rigorous and well-coordinated way.

On the other hand, predictions of water fluxes are not coherent among models and much debate is going on regarding the realism of their representation of decadal variability. One could also argue that the relief phase is just one higher-level realization of the illusion phase, and that the true value can change either because relevant questions can change or because new observational evidence changes the conceptual meaning of a 'true' value.

The different phases of progress in modeling may force us to separate the concept of uncertainty from that of unknown. Climate sensitivity (i.e., the change in global temperature for a doubling of atmospheric CO_2) is an uncertainty because it is well understood, it has been constrained by a number of observations, and the range of model results that reproduce observations reflects the current state of knowledge. The response of the terrestrial biosphere to elevated CO_2 is an unknown because the processes are poorly understood, model results are not constrained by observations, and the community cannot distinguish which path is more likely than the other.

In the case of the terrestrial biosphere, it is possible to set upper limits based on the

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extreme cases of total land deforestation and total land reforestation [*House et al.*, 2001; but this is different from an uncertainty. An unknown requires new knowledge to be resolved. A better separation of the components of Earth system models which are unknown at a given time from those for which we can already quantify an uncertainty may help to better identify the likely (or the unlikely but dangerous) path of evolution of climate while continuing to encourage creativity and progress in science.

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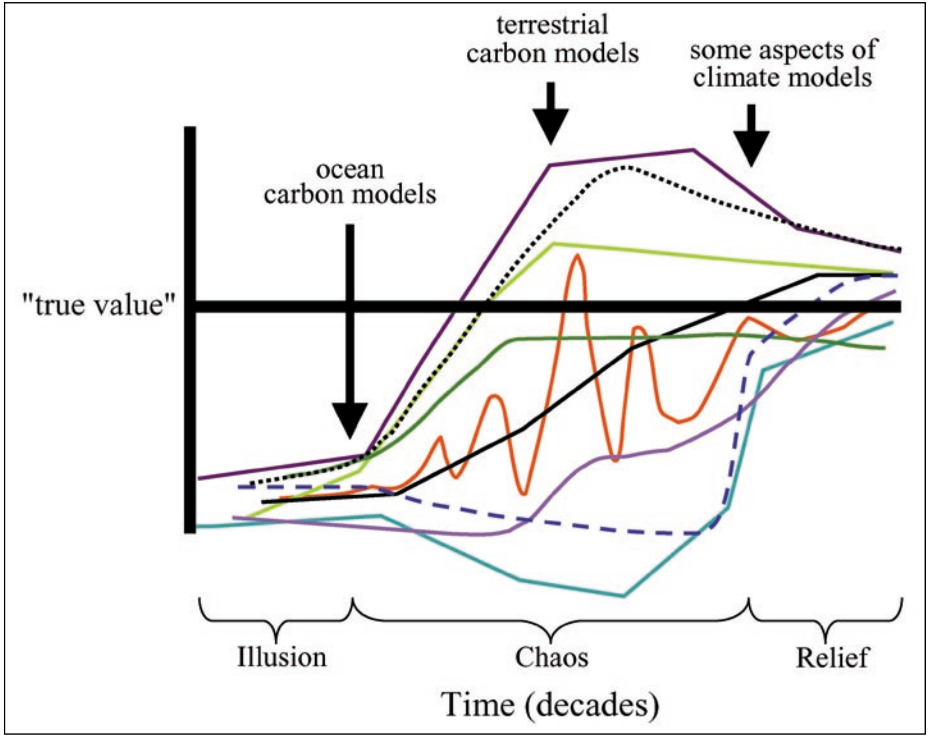

Fig. 1. Schematic of the phases of illusion, chaos, and relief in modeling. The different lines represent the time evolution of results within one model. The 'true value' on the y-axis represents the answer to a question to be addressed by a category of models. For example, what is the climate sensitivity of the Earth?

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