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Predicting Climate Change: Lessons From Reductionism, Emergence, and the Past

PAGES 111–112

Climate and Earth system models are the only tools used to make predictions of future climate change. Such predictions are subject to considerable uncertainties, and understanding these uncertainties has clear and important policy implications. This Forum highlights the concepts of reductionism and emergence, and past climate variability, to illuminate some of the uncertainties faced by those wishing to model the future evolution of global climate.

General circulation models (GCMs) of the atmosphere-ocean system are scientists' principal tools for providing information about future climate. GCMs consequently have considerable influence on climate change–related policy questions. Over the past decade, there have been significant attempts, mainly by statisticians and mathematicians, to explore the uncertainties in model simulations of possible futures, accompanied by growing debate about the interpretation of these simulations as aids in societal decisions. In this Forum, we discuss atmosphere-ocean GCMs in the context of reductionist and emergent approaches to scientific study.

Emergence and Reductionism

In 1972, the physicist Philip Anderson, then at Cambridge University, United Kingdom, wrote an influential paper in which he argued that a methodological barrier existed in physics, preventing fruitful interactions between particle and condensed matter physics [*Anderson*, 1972]. He used the concepts of reductionism and emergence to explain the nature of this problem. We believe that a similar conceptual approach could illuminate contemporary issues in climate science, particularly regarding the analysis and presentation of model-based projections of future climate change.

Reductionism argues that deterministic approaches to science and positivist views of causation are the appropriate methodologies for exploring complex, multivariate systems. It suggests that cause and effect relations are bound by linearity and that such "one-to-one" relationships [*Bohm*, 1957] thus allow perfect prediction and retrodiction, given perfect knowledge of the initial conditions. This paradigm suggests that system behavior can be reduced to a set of quantitative laws governing the behavior of basic forces and a few basic elementary particles.

The difficulty of moving between the scales, as expressed elegantly by Anderson, is that a successful reductionist explanation need not imply the possibility of a successful constructionist approach, i.e., one where the behavior of a complex system can be deduced from the fundamental reductionist understanding. Rather, large, complex systems may be better understood, and perhaps only understood, in terms of observed, emergent behavior [*Schweber*, 1993]. The practical implication is that there exist system behaviors and structures that are not amenable to explanation or prediction by reductionist methodologies [*Casti*, 1996; *Harrison*, 2001; *Willis and Whittaker*, 2002].

Complex climate models can be viewed as a combination of the reductionist and emergent approaches. The dynamics of fluid motion on a rotating planet receive an essentially reductionist approach, while small-scale processes (e.g., gravity waves), phase change processes (e.g., clouds), and chemical processes have aspects of an emergent approach in that they are based on parameterization schemes where processes that occur at scales smaller than the model structure are simplified in the model. Nevertheless, it is usually assumed that representing these small-scale processes at grid box scales will generate the appropriate larger-scale behavior and that higher resolution will lead to improved representation; this is an essentially reductionist belief. For emergent properties, this would not be the case.

Barriers to the application of computer-based models of environmental systems as forecasting tools have been discussed for some time [e.g., *Oreskes et al.*, 1994]. Attempts have been made to categorize the uncertainties in such programs. *Kennedy and O'Hagan* [2001], for instance, discuss generic sources of model uncertainty, while *Stainforth et al.* [2007] focus specifically on uncertainties in climate forecasting. Fundamental issues of interpretation of model outputs also are being increasingly discussed and debated [*Smith*, 2002; *McWilliams*, 2007].

Experiments exploring uncertainties in model-based simulations of the 21st century have tended to focus on uncertainties in the way physical processes are represented using multimodel [*Tebaldi et al.*, 2005; *Meehl et al.*, 2007] and perturbed physics [*Allen and Stainforth*, 2002; *Murphy et al.*, 2004] ensembles. *Stainforth et al.* [2007] argue for model ensembles that also address the uncertainty of conditions related to the initial state of the system more comprehensively. Yet even such grand ensembles are based solidly on the reductionist foundation of the models they use.

Past Climate Change

The study of past climate may be critical in identifying emergent phenomena as well as important in guiding speculation on the reliability of climate models and the assessment of future risks. The Holocene (the past ~10,000 years) has so far been a period of relative climatic stability; there has been no change in climatic forcing comparable to the doubling of atmospheric carbon dioxide (CO_2) concentrations above preindustrial levels that we are likely to see by the middle of this century. Atmospheric CO_2 concentrations are now higher than they have been for at least the past 650,000 years; human influence on the global climate is profound. That there are severe risks in the future is clear; their details and character are not.

Broecker [1999] has bemoaned the limitations of climate models in re-creating some aspects of past climates such as global temperature response, changes in dust production, or reduction in mountain snowlines. The present generation of climate models may not have captured these aspects for a number of reasons, including that experiments have not been run, the exploration of model and initial condition uncertainty has been insufficient, the model resolutions are too low, the models do not include the relevant fundamental processes, or there have not been enough intellectual and financial resources devoted to the problem of adequately modeling the past. It is also possible that such aspects are the result of emergent properties that simply cannot be captured by current models or potentially by any models likely to be developed in the next few decades. Information on how climate has changed in the past may therefore be of direct relevance in evaluating risks of climate change in the 21st century by providing context for model-based information for that period and by helping us understand the emergent processes that are important in observed features of past climate.

It is not clear whether future advances in climate prediction and modeling will be based upon assessments of emergent processes and phenomena, or whether these approaches will be superseded by an essentially reductionist approach as our knowledge of the physical processes grows larger. Although reductionism has allowed us to make considerable strides in our understanding of the chemistry of atmospheric processes, radiation transfer, and the development of high-resolution dynamical modeling, the lessons from other scientific disciplines appear to be that there exist limits to our understanding of complex systems. Such limits have been explored in subjects such as mathematics and computer science, and if similar limits to knowledge apply to the climate system, then our reliance on emergence as an explanatory device may well remain.

Rial et al. [2004, p. 30] argued, "[S]ince the climate system is complex, occasionally chaotic, dominated by abrupt changes and driven by competing feedbacks with largely unknown thresholds, climate prediction is difficult, if not impracticable." The inability of our climate and Earth system models to mimic rapid climate shifts in the past (and some significant elements of the present climate system) does not negate their value in informing society about possible futures. However, it does suggest that these models may not be preparing us for some possible responses.

We know that climate change in the past has sometimes been rapid [*Alley et al.*, 2003]. A crucial issue is whether future change could display similar characteristics.

This would pose severe challenges—not illustratable using today's models—for our ability to manage and adapt.

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References

Allen, M. R., and D. A. Stainforth (2002), Towards objective probabilistic climate forecasting, *Nature*, *419*, 228.
Alley, R. B., et al. (2003), Abrupt climate change, *Science*, *299*, 2005–2010.
Anderson, P. W. (1972), More is different: Broken symmetry and the nature of the hierarchical structure of science, *Science*, *177*, 393–396.
Bohm, D. (1957), *Causality and Chance in Modern Physics*, Routledge, London.
Broecker, W. S. (1999), What if the conveyor were to shut down? Reflections on a possible outcome of the great global experiment, *GSA Today*, *9*(1), 1–7.
Casti, J. L. (1996), The outer limits: In search of the "unknowable" in science, in *Boundaries and Barriers on the Limits to Scientific Knowledge*, edited by J. L. Casti and A. Karlqvist, pp. 12–26, Addison-Wesley, Boston, Mass.
Harrison, S. (2001), On reductionism and emergence in geomorphology, *Trans. Inst. Br. Geogr.*, *26*, 327–339.
Kennedy, M. C., and A. O'Hagan (2001), Bayesian calibration of computer models, *J. R. Stat. Soc., Ser. B*, *63*, 425–450.
McWilliams, J. C. (2007), Irreducible imprecision in atmospheric and oceanic simulations, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 8709–8713.
Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007), The WCRP CMIP3 multimodel dataset: A new era in climate change research, *Bull. Am. Meteorol. Soc.*, *88*, 1383–1394.
Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth (2004), Quantification of modelling uncertainties in a large ensemble of climate change simulations, *Nature*, *430*, 768–772.
Oreskes, N., K. Shrader-Frechette, and K. Belitz (1994), Verification, validation, and confirmation of numerical models in the Earth sciences, *Science*, *263*, 641–646.
Rial, A., et al. (2004), Nonlinearities, feedbacks and critical thresholds within the Earth's climate system, *Clim. Change*, *65*, 11–38.
Schweber, S. S. (1993), Physics, community and the crisis in physical theory, *Phys. Today*, *46*, 34–39.
Smith, L. A. (2002), What might we learn from climate forecasts?, *Proc. Natl. Acad. Sci. U. S. A.*, *4*(99), 2487–2492.
Stainforth, D. A., M. R. Allen, E. R. Tredger, and L. Smith (2007), Confidence and uncertainty and decision-support relevance in climate predictions, *Philos. Trans. R. Soc., Ser. A*, *365*, 2145–2161.
Tebaldi, C., R. L. Smith, D. Nychka, and L. O. Mearns (2005), Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multimodel ensembles, *J. Clim.*, *18*, 1524–1540.
Willis, K. J., and R. J. Whittaker (2002), Species diversity—Scale matters, *Science*, *295*, 1245–1248.

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MEETING

Investigating Arctic Ocean History: From Speculation to Reality

A Workshop to Prepare for Arctic Ocean Scientific Drilling; Bremerhaven, Germany, 3–5 November 2008

PAGES 112–113

The modern Arctic Ocean appears to be changing faster than any other region. To understand the potential extent of high-latitude climate change, it is necessary to sample the history stored in the sediments filling the basins and covering the ridges of the Arctic Ocean. These sediments have been imaged with seismic reflection data, but except for the superficial record, which has been piston cored, they have been sampled only in a few locations. In November 2008 a meeting was held at the Alfred Wegener Institute, in Germany, to plan the future of scientific drilling in the Arctic Ocean.

One hundred forty-one applications were received for the 95 available seats. The Consortium for Ocean Leadership provided support for the workshop through the U.S. Science Support Program associated with the Integrated Ocean Drilling Program (IODP) and through the Nansen Arctic Drilling Program. In addition to these funds, contributions from the European Science Foundation supported European and American participants. The Arctic Ocean Sciences Board and contributions from six oil companies (BP, ConocoPhillips, ExxonMobil, the Norwegian Petroleum Directorate, Shell, and Statoil) made it possible to support Canadian, Russian, Japanese, and Korean participants.

In planning this meeting, the conveners attempted to mesh the Arctic science and ocean drilling communities. To develop a common reference frame, the first day of the meeting focused on presentations about what is known about the Arctic Ocean; the limited history of high-latitude drilling, which includes a core taken on the Lomonosov Ridge in 2004 during the Arctic Coring Expedition (ACEX; IODP Leg 302) and a core collected in 1993 below the ice-free waters of the Yermak Plateau to the north of Svalbard (Ocean Drilling Program (ODP) Leg 151); and the process of developing proposals for IODP. The next day and a half was spent in breakout groups discussing the questions to be addressed by drilling and targets for Arctic scientific drilling.

On the final day, the participants committed to submitting new IODP preproposals for Arctic Ocean drilling. On the basis of this discussion at this meeting, approximately six new preproposals may be submitted to IODP by the 1 April deadline. In addition, a community-wide (United States, Europe, Japan, and others), multidisciplinary, and international conference—IODP New Ventures in Exploring Scientific Targets (INVEST)—is planned for September 2009 to discuss directions of scientific ocean drilling beyond 2013.

The IODP drilling proposals discussed at the recent workshop will be submitted at a critical time for both the future of Arctic Ocean science and the future of scientific ocean drilling. Only in the past few years, through dedicated efforts of a number of research groups, have there been sufficient data to propose testable hypotheses and to select drill sites on most of the significant bathymetric features. Meeting conveners hope these preproposals will direct future scientific ocean drilling north toward these critical priorities, and that the results of the recent workshop will contribute to developing new scientific objectives.

Many of the workshop's talks, documents generated by the breakout groups, and contact information for the IODP preproposals are available through the meeting Web site (http://www.oceanleadership.org/usssp/workshops/arctic). More information on the upcoming INVEST conference can be found at http://www.iodp.org.

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