

The physics of climate modeling

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Climate is a large-scale phenomenon that emerges from complicated interactions among small-scale physical systems. Yet despite the phenomenon's complexity, climate models have demonstrated some impressive successes.

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Climate projections made with sophisticated computer codes have informed the world's policymakers about the potential dangers of anthropogenic interference with Earth's climate system. Those codes purport to model a large part of the system. But what physics goes into the models, how are the models evaluated, and how reliable are they?

The task climate modelers have set for themselves is to take their knowledge of the local interactions of air masses, water, energy, and momentum and from that knowledge explain the climate system's large-scale features, variability, and response to external pressures, or "forcings." That is a formidable task, and though far from complete, the results so far have been surprisingly successful. Thus, climatologists have some confidence that theirs isn't a foolhardy endeavor.

Climate modeling derives from efforts first formulated in the 1920s to numerically predict the weather. However, it wasn't until the 1960s that electronic computers were able to meet the extensive numerical demands of even a minimal description of weather systems. Since then, ever more components have been added to climate models—land, oceans, sea ice, and more recently, interactive atmospheric aerosols, atmospheric chemistry, and representations of the carbon cycle. Indeed, a significant part of the interdisciplinary work needed to understand climate change is being driven by climate model development. Today's models are flexible tools that can answer a wide range of questions, but at a price: They can be almost as difficult to analyze and understand as the real world.

Basic physics, emergent behavior

The physics in climate models can be divided into three categories. The first includes fundamental principles such as the conservation of energy, momentum, and mass, and processes, such as those of orbital mechanics, that can be calculated from fundamental principles. The second includes physics that is well known in theory, but that in practice must be approximated due to discretization of continuous equations. Examples include the transfer of radiation through the atmosphere and the Navier-Stokes equations of fluid motion. The third category contains empirically known physics such as formulas for evaporation as a function of wind speed and humidity.

For the latter two categories, modelers often develop parameterizations that attempt to capture the fundamental phenomenology of a small-scale process. For instance, the average cloudiness over a 100-km² grid box is not cleanly related to the average humidity over the box. Nonetheless, as the average humidity increases, average cloudiness will also increase. That monotonic relationship could be the basis for a

parameterization, though current schemes are significantly more complex than my example.

Given the nature of parameterizations among other features, a climate model depends on several expert judgment calls. Thus, each model will have its own unique details. However, much of the large-scale behavior projected by climate models is robust in that it does not depend significantly on the specifics of parameterization and spatial representation.

The most interesting behavior of the climate system is emergent. That is, the large-scale phenomena are not obvious functions of the small-scale physics but result from the complexity of the system. For instance, no formula describes the Intertropical Convergence Zone of tropical rainfall, which arises through a combination of the seasonal cycle of solar radiation, the properties of moist convection, Earth's rotation, and so on. Emergent qualities make climate modeling fundamentally different from numerically solving tricky equations.

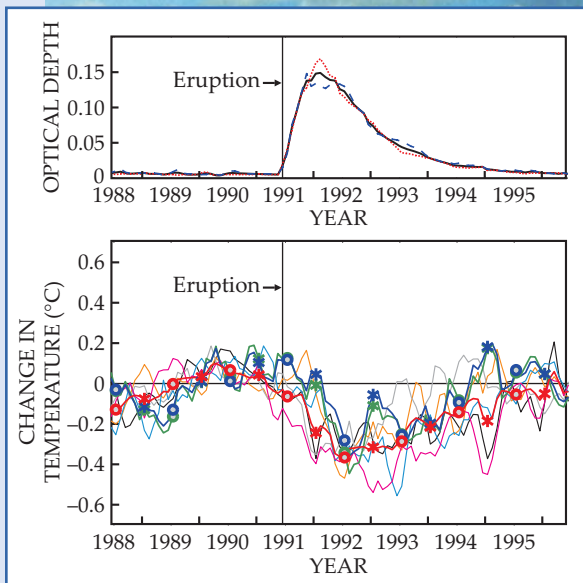
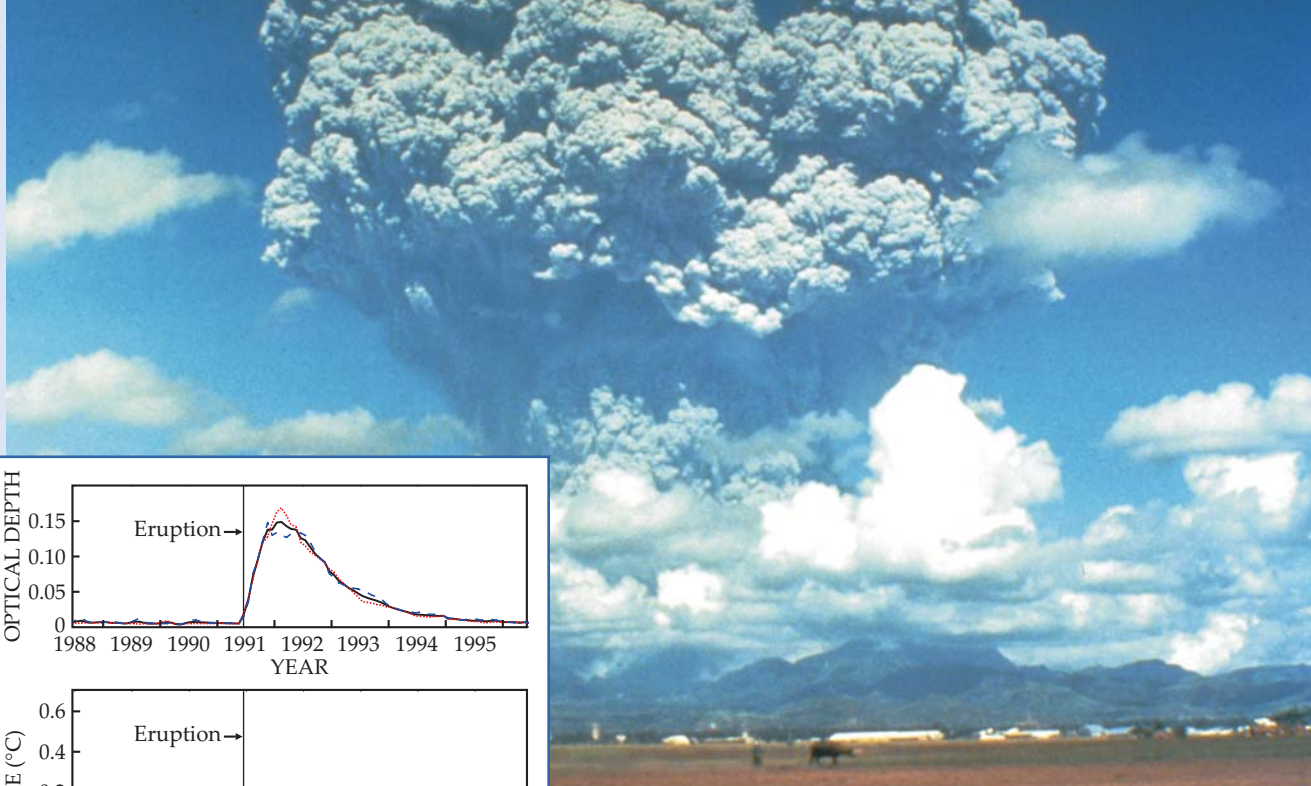
Climate modeling is also fundamentally different from weather forecasting. Weather concerns an initial value problem: Given today's situation, what will tomorrow bring? Weather is chaotic; imperceptible differences in the initial state of the atmosphere lead to radically different conditions in a week or so. Climate is instead a boundary value problem—a statistical description of the mean state and variability of a system, not an individual path through phase space. Current climate models yield stable and nonchaotic climates, which implies that questions regarding the sensitivity of climate to, say, an increase in greenhouse gases are well posed and can be justifiably asked of the models. Conceivably, though, as more components—complicated biological systems and fully dynamic ice-sheets, for example—are incorporated, the range of possible feedbacks will increase, and chaotic climates might ensue.

Testing climate models

Model assessment occurs on two distinct levels—the small scale at which one evaluates the specifics of a parameterization and the large scale at which predicted emergent features can be tested. The primary test bed is the climate of the present era, particularly since 1979, when significant satellite data started to become readily available.

The 1991 eruption of Mount Pinatubo provided a good laboratory for model testing (see the figure). Not only was the subsequent global cooling of about 0.5 °C accurately forecast soon after the eruption, but the radiative, water-vapor, and dynamical feedbacks included in the models were quantitatively verified.

More than a dozen facilities worldwide develop climate models, whose ability to simulate the current climate has im-



The 1991 eruption of Mount Pinatubo in the Philippines (above) produced sulfate aerosols that affected climate for years and offered climate modelers an unprecedented opportunity to compare models with observations. The upper graph shows the atmospheric concentration of aerosols as measured by the optical depth, an indication of the atmosphere's ability to block radiation transmission (in this case, at 500 nm). The black solid curve gives the global mean; broken curves describe the Northern (red) and Southern (blue) hemispheres. The lower graph gives global mean surface temperature. The green and purple curves were generated from two somewhat different observational data sets. The red curve gives the average of five runs simulated by the GISS ModelE GCM. Circles indicate June–August; asterisks, December–February. (Photograph by Dave Harlow, courtesy of the US Geological Survey; graphs adapted from J. Hansen et al., <http://arxiv.org/abs/physics/0610109>.)

proved measurably over the past 20 years. Interestingly, the average across all models almost invariably outperforms any single model, which shows that the errors in the simulations are surprisingly unbiased. Significant biases common to most models do exist, however—for instance, in patterns of tropical precipitation.

Climate modelers are particularly interested in testing the variability of their models. Some variability is intrinsic, but modelers also study variability caused by changes in external forcings, such as in Earth's orbit or in solar activity. Those studies are complicated by incomplete observations, the nature of satellite data, uncertainties in the forcings, and other issues.

The most comprehensive comparison of models ever conducted is now under way using simulations that were performed in 2004 and 2005 for the Intergovernmental Panel on Climate Change. Those simulations for the 20th century and beyond are being examined by hundreds of independent teams who will assess the robustness of the results and help illuminate persistent problems.

Many challenging climate questions remain unanswered. Examples include how climate conditions influence El Niño; how responses can be predicted at the regional scale; and how simulations of rare, extreme events such as hurricanes and heat waves can be validated. Such issues may require better encapsulations of, for example, the turbulent behavior of the near-surface atmosphere, the effects of ocean eddies, or the microphysics of clouds and aerosols. The im-

plementation of more sophisticated parameterizations and the ongoing increases in resolution as computer resources increase suggest that models will continue to improve. However, many results, such as the warming effect of increasing greenhouse gases that was first demonstrated in much simpler models decades ago, have proved extremely robust.

Climate models are unmatched in their ability to quantify otherwise qualitative hypotheses and generate new ideas that can be tested against observations. The models are far from perfect, but they have successfully captured fundamental aspects of air, ocean, and sea-ice circulations and their variability. They are therefore useful tools for estimating the consequences of humankind's ongoing and audacious planetary experiment.

Additional resources

- Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, http://www.grida.no/climate/ipcc_tar/wg1.
- IPCC Model Output, http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php.
- National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory, <http://www.gfdl.noaa.gov>.
- National Center for Atmospheric Research, <http://www.ncar.ucar.edu>.
- RealClimate Blog, <http://www.realclimate.org>. ■