Tropical storm systems confound conventional climate models but might yield to stochastic simulations.

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A touch of the random

As researchers seek ever-larger supercomputers to crunch climate models of baffling complexity, some are calling for a fresh, statistics-based approach

By **Colin Macilwain**

Three statisticians go hunting and flush a duck. The first shoots high, over the bird's head. The second aims too low and sends a bullet whistling meters below the duck's belly. So the third statistician jumps up and down yelling, "We got him! We done got him!"

Not the best way to bag waterfowl, perhaps—but in their own habitat, researchers have found similar scattershot methods very effective for predicting the behavior of complex systems. "Stochastic" techniques, in which computer simulations spit out clouds of possible outcomes, have been widely applied in economics, physics, engineering, and weather forecasting. They have not found a home, however, in one of the highest profile and most contentious areas of forecasting: climate modeling.

There, researchers have usually aimed for a deterministic solution: a single scenario for how climate will respond to inputs such as greenhouse gases, obtained through increasingly detailed and sophisticated numerical simulations. The results have been scientifically informative—but critics charge that the models have become unwieldy, hobbled by their own complexity. And no matter how complex they become, they struggle to forecast the future.

"The house used to have two floors. Now it has eight. It is bearing all this weight, and cracks are appearing in the walls," says Christian Jakob, a climate modeler based at Monash University, Clayton, in Australia. "That gives you two choices," Jakob says. "You can go in and strengthen the foundations. Or maybe, it's time to build a new house."

Now, some researchers are calling for a major overhaul: The models, they say, should be remodeled along stochastic lines. Later this month, for example, a special issue of the *Philosophical Transactions of the Royal Society A* will publish 14 papers setting out a framework for stochastic climate modeling.

One key reason climate simulations are bad at forecasting is that it's not what they were designed to do. Researchers devised them, in the main, for another purpose: exploring how different components of the

system interact on a global scale. The models start by dividing the atmosphere into a huge 3D grid of boxlike elements, with horizontal edges typically 100 kilometers long and up to 1 kilometer high. Equations based on physical laws describe how variables in each box—mainly pressure, temperature, humidity, and wind speed—influence matching variables in adjacent ones. For processes that operate at scales much smaller than the grid, such as cloud formation, scientists represent typical behavior across the grid element with deterministic formulas that they have refined over many years. The equations are then solved by crunching the whole grid in a supercomputer.

The approach has proven itself very useful for probing the workings of Earth's climate system—how fossil fuel emissions, atmospheric carbon dioxide, and global temperatures all interact, for example. But it falls short when asked to predict where, when, and how severely future climate changes will unfold.

Last year, for example, scientists on the Intergovernmental Panel on Climate Change (IPCC) systematically compared the predic-

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tions of 20 major climate models against the past 6 decades of climate data. The results were disappointing, says Ben Kirtman, a climate scientist at the University of Miami in Florida and coordinating author of the near-term predictability chapter of last year's fifth IPCC assessment report. The models performed well in predicting the global mean surface temperature and had some predictive value in the Atlantic Ocean, but they were virtually useless at forecasting conditions over the vast Pacific Ocean.

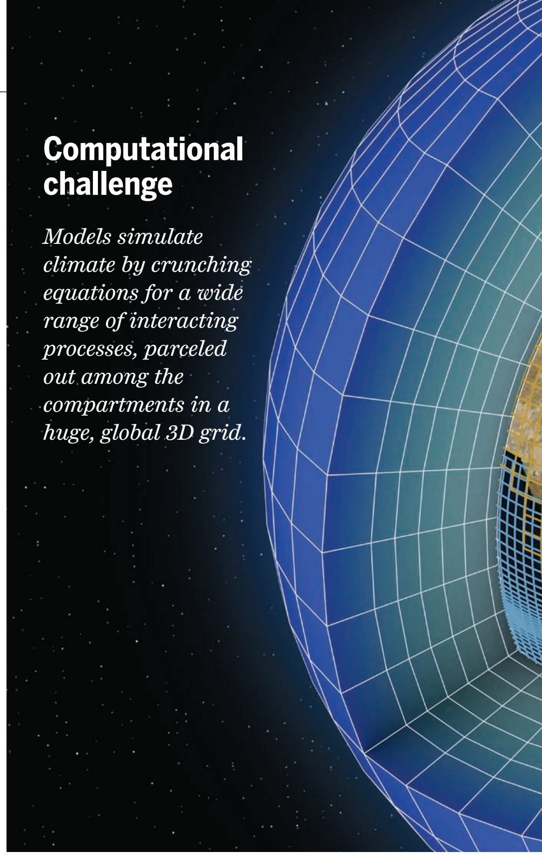
The most comprehensive models aren't necessarily the most useful ones, Kirtman says. As climatologists keep adding components to simulate processes as detailed as leaf growth and termite distribution, the models have become bloated with features and run sluggishly without making better predictions. "It's a fundamental problem," he says. "They keep trying to add in everything." And parts of the models don't simulate nature well at all, Jakob adds: "Some of the old problems have not been solved. On things like simulating rainfall and cloud formation, progress has been painfully slow."

Much of the problem boils down to grid resolution. "The truth is that the level of detail in the models isn't really determined by scientific constraints," says Tim Palmer, a physicist at the University of Oxford in the United Kingdom who advocates stochastic approaches to climate modeling. "It is determined entirely by the size of the computers." Roughly speaking, an order-of-magnitude increase in computer power is needed to halve the grid size. Typical horizontal grid size has fallen from 500 km in the 1970s to 100 km today and could fall to 10 km in 10 years' time. But even that won't be much help in modeling vitally important small-scale phenomena such as cloud formation, Palmer points out. And before they achieve that kind of detail, computers may run up against a physical barrier: power consumption. "Machines that run exaflops [10^{18} floating point operations per second] are on the horizon," Palmer says. "The problem is, you'll need 100 MW to run one." That's enough electricity to power a town of 100,000 people.

Faced with such obstacles, Palmer and others advocate a fresh start. Climate modelers, they say, need to step backward and draw some inspiration from weather forecasting—specifically techniques developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, U.K.

Starting in the 1990s, researchers at ECMWF shook up weather forecasting worldwide by introducing stochastic approaches into their models. Also known as Monte Carlo methods, these techniques were first developed by physicists in the World War II Manhattan Project to model how neutrons diffuse through materials, bouncing off atomic nuclei as they go—a process they had struggled to model deterministically. The idea is analogous to repeatedly rolling dice or spinning a roulette wheel: Run the calculations many times to produce a range of different outcomes, then "tune" the model by aggregating the results and comparing them with empirical observations. Researchers can extend the "hindcasts" into the future to make predictions expressed as probabilities, with uncertainties plainly evident in the scatter of results. Such techniques are widely used today in many branches of physics and engineering, by insurers calculating risk, and even by computational biologists to model cell membranes or proteins.

To apply the method to weather forecasting, the ECMWF modelers introduced small, random perturbations in the initial weather conditions. By running its model many times with slightly different initial conditions—an approach known as ensemble modeling—the center produced



Computational challenge

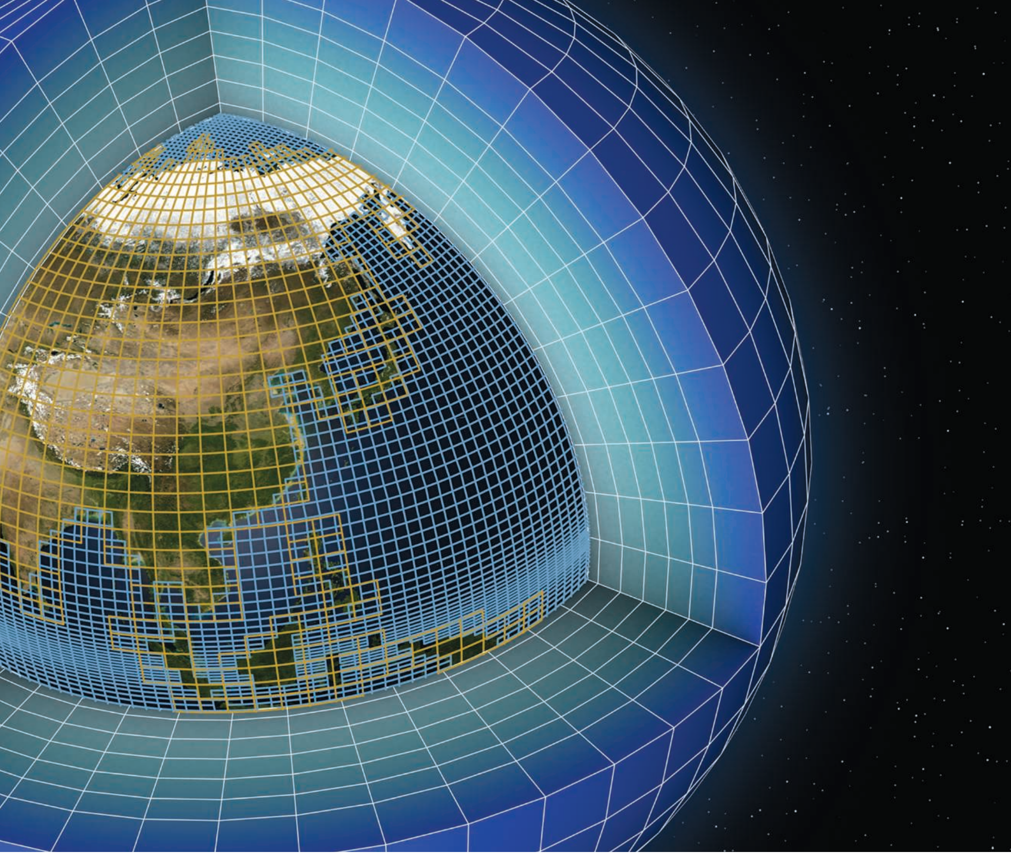
Models simulate climate by crunching equations for a wide range of interacting processes, parceled out among the compartments in a huge, global 3D grid.

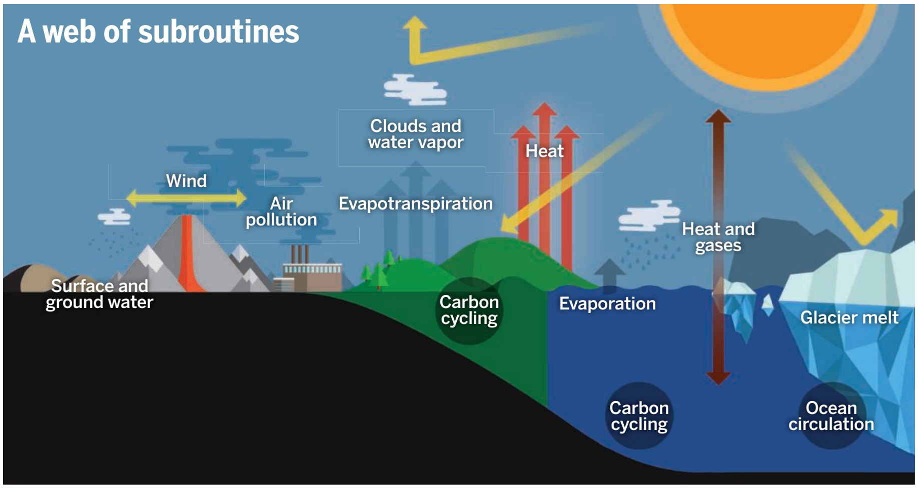
superior weather forecasts. The approach has been adopted by most major weather forecasters worldwide.

Palmer, who led the development of the ensemble approach at ECMWF, says closely related approaches could transform climate modeling. One major difference is in timescale: Unlike weather modelers, who quickly find out whether their predictions were correct, climate researchers think decades ahead. To tune a model, they must feed it climate records up to a certain year—say, 1990—and see how well it would have predicted climate patterns for the decade that followed.

Stochastic models, Palmer says, could get a grip on components of the climate system that are too slippery for traditional deterministic models to handle. For example, tropical thunderstorm systems—each of which can release the energy of a hydrogen bomb—are "crucially important" in the global climate system, he says. But because their cores are only a few kilometers wide, ordinary model grids can't capture them, and the fixed mathematical descriptions on which they rely contain "significant errors" that a probabilistic approach would avoid, Palmer says.

In the special issue of *Philosophical Transactions A*, researchers propose several complementary approaches to incorporate such approaches into climate models. The ideas include building supercomputers to work faster by allowing some stochastic errors at the transistor level, and modeling different processes on different scales to ease the computational burden.





In another approach, modelers would take a particular component of existing climate models, such as a subroutine that simulates cloud formation, and replace it with a stochastic equivalent. In an unpublished study submitted to the *Journal of the Atmospheric Sciences*, Andrew Majda, a mathematician at New York University's Courant Institute of Mathematical Sciences in New York City, and colleagues did just that. He showed that slotting a stochastic cloud simulation into a National Center for Atmospheric Research (NCAR) climate model could closely reproduce an important tropical weather pattern that numerical models have struggled to capture.

In the pattern, known as the Madden-Julian Oscillation (MJO), rainfall sweeps eastward across the Indian and Pacific oceans every 30 to 60 days. The researchers used a stochastic process called a Markov chain to capture the behavior of various types of clouds. Plugged into NCAR's High-Order Methods Modeling Environment (HOMME), the probabilistic simulation "drastically improves the results of the deterministic model," the authors say. Among other real-world characteristics that conventional models fail to capture, the souped-up HOMME model correctly forecasts the MJO's propagation speed and its tendency to spawn "trains" of two or even three such weather patterns in quick succession.

Some researchers believe such approaches can be fully tested only by building entirely new climate models. "Ideally, I think we will need to go back and design the models from scratch," Palmer says. "You really want to build the stochasticity in at a fundamental level, to make it more consistent with the underlying laws of physics."

Others would go still further and predict climate change purely on the basis of statistical data from the climate record. Last year in the *Journal of Climate*, Leonard Smith of the London School of Economics and Political Science and his colleague Emma Suckling reported the results of an experiment in which they took global climate data for various locations over the past half-century, fed it into the most prominent climate models, and compared the predictions with those of a very simple statistical model that extrapolated the future climate from that of the recent past. The simple model—which worked by taking mean-temperature changes for periods of 1 to 10 years over the past century and using these to extrapolate the future—fared best, Smith says.

Supporters of deterministic modeling say they are not about to abandon an approach they consider tried and trusted. Existing climate models are "continuously scrutinized in the scientific literature" and pass muster, says Erland Källén, a veteran climate modeler and director of research at ECMWF. And Chris Bretherton of the University of Washington, Seattle, who chaired a 2012 study of climate models by the U.S. National Research Council, says critics of existing models have yet to present convincing evidence that stochastic modeling could do a better job. "There's a feeling that it is a valid approach. But I don't think that there's a consensus that we'll need to have stochastical parameterization," he says.

Advocates of stochastic approaches, however, say only a drastic change of course can jolt predictive climate modeling out of its current rut. With policymakers clamoring for robust forecasts of how temperature and precipitation will change region by region in coming decades, Smith says, time is running out: "The question is, when will we have significantly better quality information than we have today? I think we may have our answer from the climate before we get it from the physics."

With current physics-based models struggling to predict the climate a decade or two out, modelers may be inclined to give stochastic methods a roll of the dice—especially as better tools emerge for testing models against the climate record. "We need to be unforgiving," says Miami's Kirtman, and "make hard-nosed comparisons" of models' predictive performance. "I think we still have an enormous amount to learn." ■

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