UCAR Quarterly Spring 2007

The math behind geoscience

IMAGe champions cross-cutting models and methods

by Bob Henson

"We get to dabble in everything. It's like a big banquet of problems," says Doug Nychka. He's referring to the Institute for Mathematics Applied to Geosciences (IMAGe), whose influence stretches across much of NCAR and along many paths in the geoscience community.

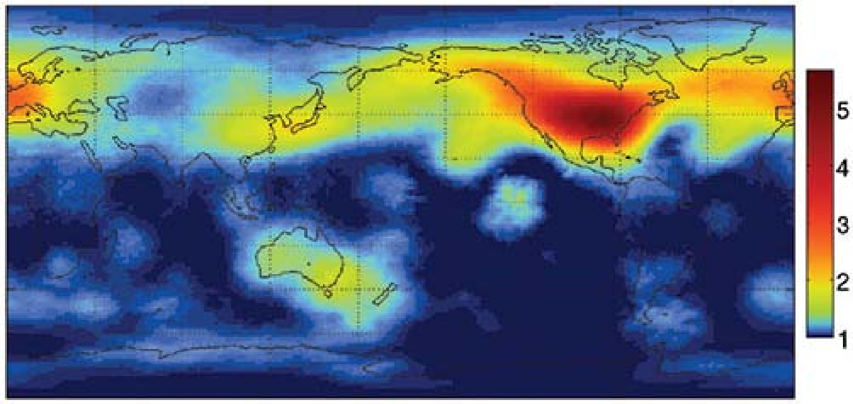
With Nychka as its founding director, IMAGe is based in NCAR's Computational and Information Systems Laboratory. Supported mainly through NSF funding, IMAGe's four groups focus on data assimilation, turbulence, geophysical statistics, and computational mathematics. Each group hosts a number of external visitors each year and conducts an active research program. Five IMAGe scientists hold joint appointments with other parts of NCAR, and the institute maintains close ties with university faculty.

One of IMAGe's main goals is to advance weather and climate modeling through the application of flexible mathematical models and methods. Nychka cites turbulence as an example that lends itself to multifaceted analysis. "It's a phenomenon that appears at many spatial scales and in different contexts," he says, adding that a common statistical framework can be applied to observations of turbulence coming from very different parts of the Earth system.

Recent high-resolution modeling of electromagnetic currents in the presence of turbulent flow, such as those observed in the solar corona and Earth's magnetosphere, depicts "roll-ups" of current sheets (the cylindrical features at the center and top of the graphic at right). These roll-ups are produced by instabilities similar to those responsible for Kelvin-Helmholtz clouds (above). (Illustration courtesy IMAGe; photo by Benjamin Foster.)

Although IMAGe is little more than two years old, geophysical turbulence—whether on the Sun or in Earth's atmosphere or oceans—has been an important research topic at NCAR for decades. In many cases, the computational power to grapple with turbulence problems has arrived only recently. Now, the push is on to leverage that power and enter new realms of visualization and understanding.

IMAGe's turbulence experts made significant progress over the last year in modeling the behavior of the magnetic currents that prevail in Earth's magnetosphere and the solar corona. New NCAR software can track magnetohydrodynamic turbulence as it unfolds and decays, using a cubic grid that features more than 3.6 billion points. In one recent discovery (see illustration above), sheets of magnetic current were found to roll into swirls driven by the same instabilities that produce Kelvin-Helmholtz clouds. “These are structures that you wouldn’t discern by just looking at the physical equations,” says Nychka. The study, by NCAR’s Pablo Mininni and Annick Pouquet with David Montgomery (Dartmouth College), was published in the 15 December 2006 issue of Physical Review Letters.



This graphic shows how an ensemble data assimilation method adjusts to different densities of observations to avoid overwhelming the analysis. Higher values (an inflation factor applied to the ensemble spread) denote areas of high data density, such as along flight corridors, where less weight is thereby placed on an individual observation. (Illustration courtesy Jeff Anderson, NCAR.)

Data assimilation is another long-time NCAR activity with a major presence in IMAGe. The institute now serves as one center of expertise for scientists from across and beyond NCAR interested in the topic. IMAGe hosts the Data Assimilation Research Testbed, a software platform used to explore the infusion of data into ensemble models. One emerging technique, called adaptive inflation, involves the statisical challenge of keeping ensemble models from being overwhelmed by pockets of high data density, such as the atmospheric data collected by aircraft along common flight paths (see illustration above).

With numerous NCAR scientists now dedicated largely or fully to data assimilation, the topic is fast achieving critical mass, says Nychka. “It’s important to confront numerical models with observations in order to understand the models’ strengths and places for improvement,” he says.

Safety tips for handling climate-model output

For statisticians like Nychka, the extensive numerical modeling conducted and coordinated by NCAR offers a gold mine of raw material. “Modelers at NCAR see that they have a need for statistics,” he says, “and there are many aspects of model development where we can make a contribution.” In general, he’d like to see model testing and development done in a more systematic way, especially now that the output from weather and climate models is increasingly used in policymaking and other activities.

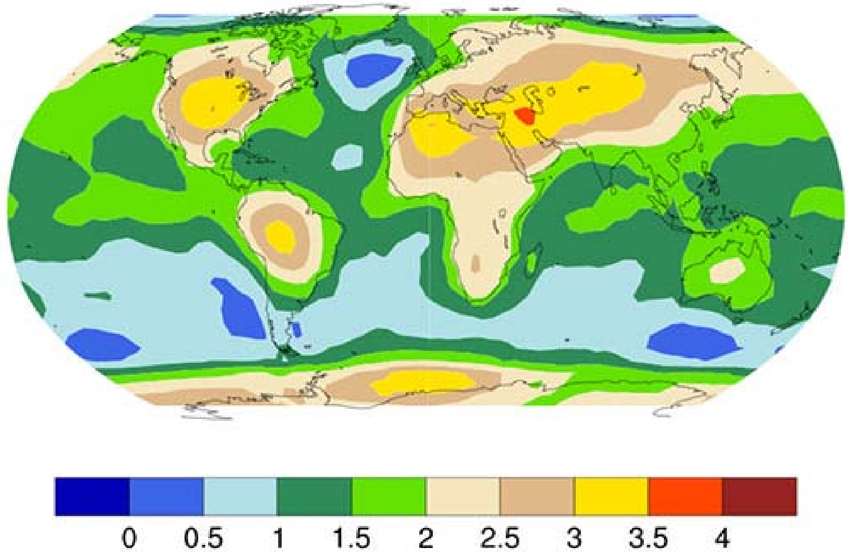
IMAGE’s group leaders include (left to right) Steve Sain, Piotr Smolarkiewicz, Jeff Anderson, and Doug Nychka, IMAGe director. Not pictured: Annick Pouquet. (Photo by Carlye Calvin.)

One risk for those interpreting model output is forgetting that the average of a model ensemble may not be a depiction of reality. For instance, few if any days have weather that precisely matches the climatic norm for a given day. Likewise, the weather five days from now, or the climate 50 years from now, is likely to have small-scale features obscured by the tyranny of averaging. “The ensemble is the real thing; the average is an artificial construct,” Nychka notes.

Another issue is model inbreeding—the

amount of overlap that can exist among different models that share the same goal. For example, the latest assessment by the Intergovernmental Panel on Climate Change (IPCC) draws on 21 global models. However, the actual diversity in numerical viewpoints may not be as great as that number indicates, notes Nychka, because some of these models use similar components or are variants of a common source.

There's also the problem of assumptions that every model makes. "If a bias is common to all models, this will incorrectly be considered part of the 'true' climate signal," notes Reinhard Furrer (Colorado School of Mines). While there's no airtight way to eliminate such biases, Furrer is working on ways to reduce their impact on climate analysis, as governments and businesses clamor for more specific regional guidance on climate change.



Statisticians and climate scientists are now teaming up to analyze the climate modeling carried out as part of the latest IPCC assessment. Above is a depiction of the amount of warming (in degrees Celsius) that can be expected with an 84.1% likelihood for the June–August period between 2080 and 2100 relative to 1980–2000, assuming a midrange emissions scenario (IPCC A1B). (Illustration courtesy Reinhard Furrer, Colorado School of Mines.)

Working with the latest IPCC runs, Furrer and colleagues recently produced a new array of global temperature projections showing the likelihood that average seasonal temperature will exceed a given value (see illustration above). This work builds on previous analyses by NCAR's Claudia Tebaldi and Gerald Meehl by calculating probability distribution functions (PDFs) for each grid point over the entire globe, rather than downscaling to produce regional climate projections from a single PDF. "It's really an extension of Claudia's work," says Furrer, who published the results in Geophysical Research Letters on 31 March with Reto Knutti (Swiss Federal Institute of Technology) and NCAR's Steve Sain, Nychka, and Gerald Meehl.

New TOYs

Much of IMAGe's community involvement occurs through workshops organized under a Theme-of-the-Year (TOY) structure. The workshops are held in conjunction with two NSF-sponsored centers, the Statistical and Applied Mathematical Sciences Institute and the Mathematical Sciences Research Institute. Each TOY is organized with colleagues at these centers and affiliated universities.

The first set of four TOY workshops, which focused on the interaction among scales in weather and climate models, was codirected in 2005–06 by applied mathematician Andrew Majda (New York University) and NCAR climate scientist Joseph Tribbia. This year's TOY workshops, which extend from November 2006 to July 2007, explore the statistics of numerical models. "We want to help match cutting-edge statistical methods to the needs of modelers and make statistical scientists aware of the issues that modelers face," says Nychka.

Montserrat Fuentes, a statistician at North Carolina State University, is helping organize this year's TOY. "I'm always trying to find scientists to work with and to establish joint research topics that could lead to dissertations, funding, and publications," says Fuentes. "IMAGe has

Montserrat Fuentes.

served as the perfect umbrella to accelerate the transfer of new statistical and mathematical techniques to scientific problems."

Next year's TOY will delve into geophysical turbulence, with an emphasis on applied mathematics and observational data. The codirector will be applied mathematician Keith Julien (University of Colorado). "The diversity in scales in geophysical fluid dynamics presents a great modeling challenge," says Julien. "It's one reason why these phenomena can be so difficult to understand." He expects the 2007–08 TOY workshop topics to range from observations and experiments to theoretical methods and models to computing and visualization.

IMAGe's Geophysical Statistics Project—which was launched at NCAR in the mid-1990s—continues to carry out theoretical research while maintaining an active visitor program and hosting several postdoctoral researchers. Such connections are a critical part of IMAGe, says Nychka, who is just as interested in bringing statisticians and applied mathematicians into the realm of the UCAR community as he is in bringing statistical tools to physical scientists.

"If you're a mathematical scientist, come and visit us," he says. "We'll listen to what you do, and we'll try to hook you up with a science team that can use your mathematics.