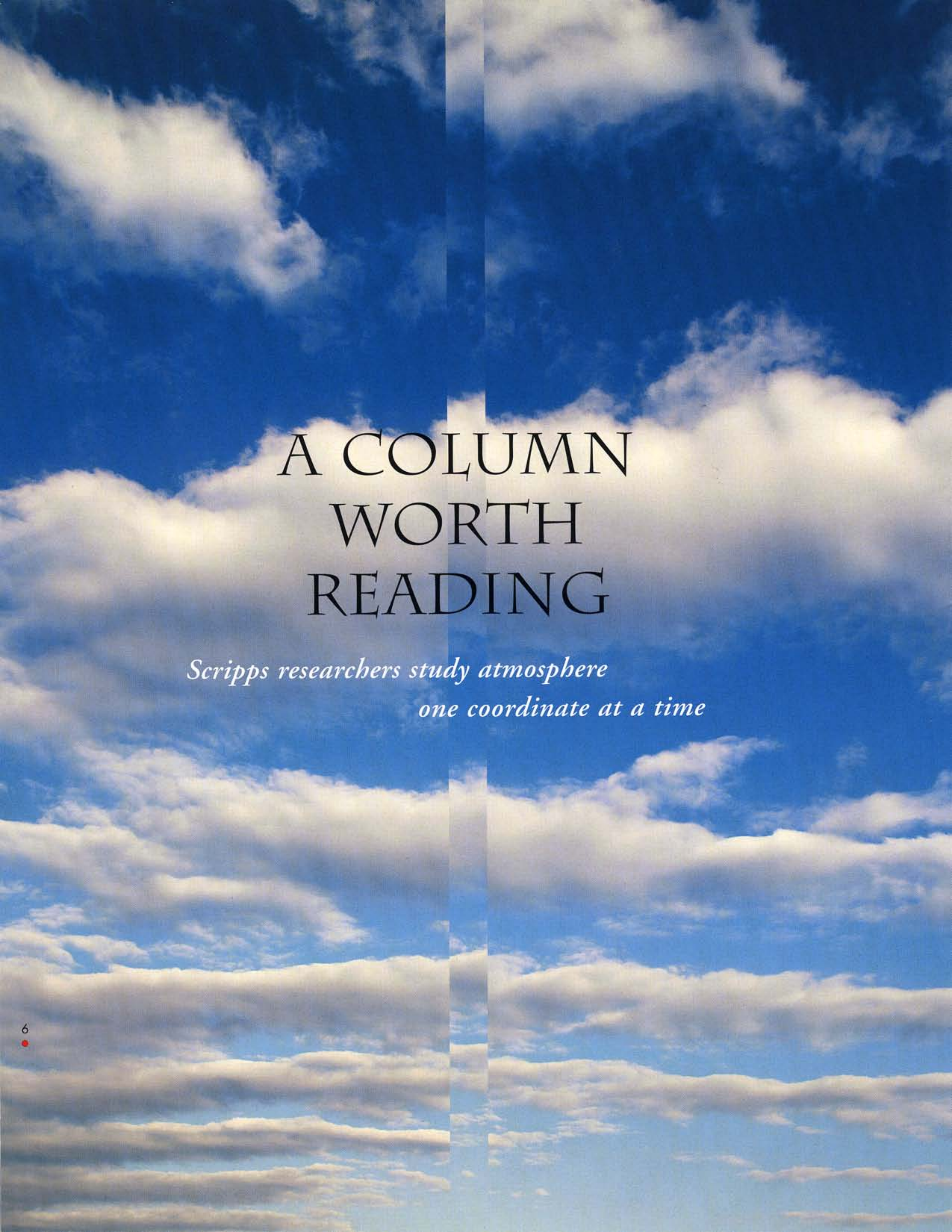


A COLUMN WORTH READING

Scripps researchers study atmosphere one coordinate at a time

MODELING

BY CHUCK COLGAN

PREDICTING THE WEATHER accurately a week in advance can be tricky. The atmosphere is far too complex for even experts to be right much more than half the time.

Now imagine trying to make forecasts for 20 years from now and even beyond. That's the task facing scientists who are tackling questions about how the buildup of atmospheric greenhouse gases such as carbon dioxide will change Earth's climate.

Determining what changes will occur is something that can only be modeled based on knowledge of how the climate system works and the record of what it has done in the past. International research efforts have led to improved computer models to take on these challenges, but according to Richard Somerville, Scripps Institution of Oceanography professor of meteorology, the models are still far from perfect.

NARROWING THE VIEW

Somerville and research associate Sam Iacobellis are taking what might be mistaken for a step backward in order to make computer models more realistic. They want to observe less of the atmosphere, not more. Somerville and Iacobellis haven't abandoned the big picture, but have found that they may learn more from narrowing their view to a smaller scale in one locale.

"The trick is to be clever enough to formulate rules for how large numbers of climate elements behave, not individually but in a statistical sense, without entering into the hopeless task of computing all of the details," Somerville said. "It's impossible to forecast individual clouds, for example, but we are learning to model the properties of entire populations of clouds."

For climate predictions, scientists use what are called "general circulation models" (GCMs), which are adapted from the same operational forecasting models used for daily and weekly weather predictions, except they are applied much further ahead. GCMs consist of hundreds of interrelated mathematical equations for key climatic variables, such as solar radiation, cloud cover, water vapor, and sea-surface temperatures.

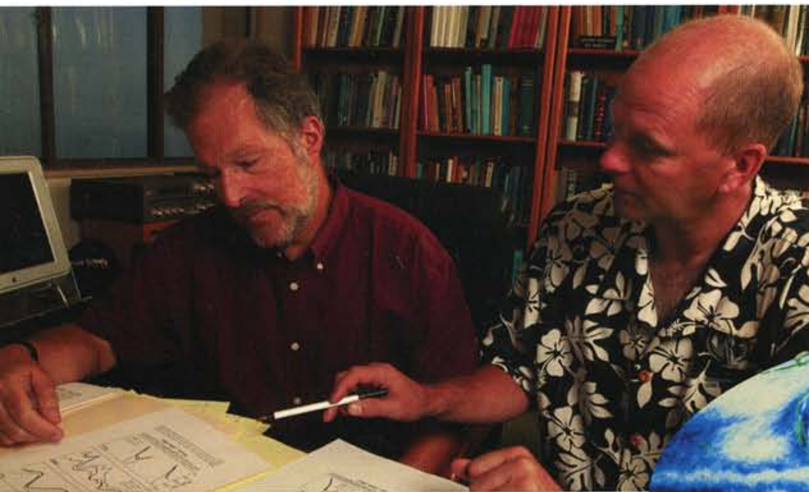
The main difference between a typical weather-forecasting model and a long-range climate model is that the latter uses a coarser spatial resolution with less detailed information so that it can simulate many years ahead using the computing capacity available today. A typical geographical prediction area, or grid box, in a climate model is 400 kilometers (250 miles) on a side, yet most climate processes occur on much smaller scales, from single clouds to individual molecules.

"The challenge is to try to determine what is going on in the small scale and translate those effects to the large-scale grid box," Iacobellis said. "We're trying to make a global model that reflects local reality."

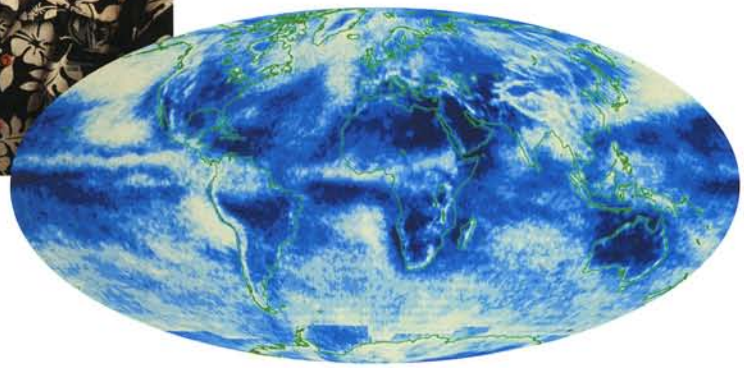
THE SINGLE-COLUMN MODEL

Somerville and Iacobellis have developed a means to refine how models account for clouds and their effects by focusing on a limited area, on the scale of 200 kilometers (125 miles). Called a "single-column model," their theoretical tool is conceptually like a soda straw extending from Earth's surface to the top of the atmosphere. Within the straw, the interactions of clouds, solar radiation, water vapor, and other conditions are calculated in detail. This approach yields more complete information on cloud radiative effects than a GCM, yet requires much less voluminous observational data and computer power. Somerville and Iacobellis compare their model's prediction with what really happens in nature. Once the single column is refined to be as realistic as possible, the resulting formulas and parameters can be transferred to a global GCM.

The key to the single-column model approach is to observe many



Left, *Richard Somerville (left) and Sam Iacobellis are refining climate models by combining improved atmospheric measurements with new techniques for data analysis.*
Below, *To test and improve their theoretical models, Somerville and Iacobellis incorporate many types of observations, including satellite imagery of global cloud cover.*



aspects of the atmosphere in great detail at one location, which is why the Atmospheric Radiation Measurement (ARM) Program is so important to their research.

ARM, created in 1989 by the Department of Energy, operates three major field stations. At the Great Plains site, which straddles the Kansas–Oklahoma border, an array of hundreds of instruments measures conventional weather variables, such as temperature, wind, and humidity, plus aspects of clouds and their interactions with radiant energy from the earth and the sun. These records are continuous in time and provide the most complete stream of data on clouds and radiation available from any observation site in the world.

CLOUDS ARE THE KEY

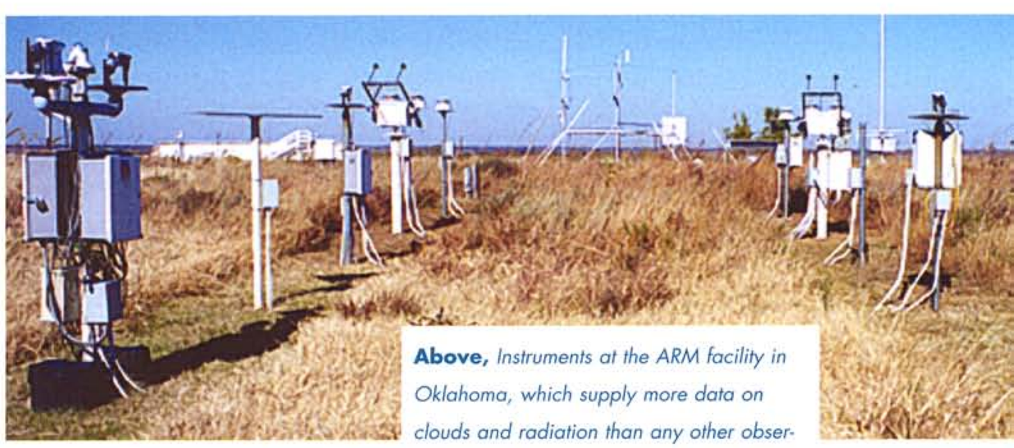
Only about 70 percent of the sunlight reaching Earth is available to drive the climate system. The remaining 30 percent is simply reflected back into space, mainly by clouds, which cover 60 percent of the planet, and by bright surfaces such as snow, ice, and deserts. This 30 percent is called the "planetary albedo."

Clouds have a dual role to play in climate: reflecting incoming sunlight and absorbing infrared radiation leaving Earth, which contributes to the greenhouse effect. Depending on their types, clouds both cool and warm the climate system. The effect of high, thin cirrus clouds is typically warming, whereas thicker, low-lying stratus clouds usually contribute more to cooling. Satellite measurements have established that the net global effect of clouds in the present climate is an overall cooling.

"However, the plain fact is that we lack a basic understanding as to how the global cloud amount, planetary albedo, and other fundamental quantities associated with clouds may have changed as our climate changed over geological time, and how they may change in the future," Somerville said. "Clouds remain the greatest single uncertainty in model forecasts of climate change."

Clouds are difficult to observe and model because they are physically complex and change rapidly over short time and space intervals. Clouds are not well represented in GCMs and are generally treated as though they were uniform horizontal features distributed evenly across a large-scale grid area.

Somerville and Iacobellis have combined their theoretical and numerical modeling skills with the expertise of ARM collaborators who specialize in improving ways to define clouds. These collaborators include Greg McFarquhar of the University of Illinois at Urbana–Champaign and David Mitchell of the Desert Research Institute in Nevada, who have studied the



Above, *Instruments at the ARM facility in Oklahoma, which supply more data on clouds and radiation than any other observation site in the world.*

small particles that make up ice clouds, typically found 10–20 kilometers (6–12 miles) above Earth's surface. The radiative properties of these clouds depend on the number, size, and shape of ice particles, which in turn are related to factors such as the amount of water in the clouds and the local temperature.

Working together, the scientists have produced more detailed and realistic representations of many cloud types. Using the single-column model, they are now able to account for clouds' microphysical and radiative properties more comprehensively than is possible with current GCMs. They have also formulated new algorithms to calculate more precisely the fluxes of solar and terrestrial radiant energy in the atmosphere.

So far, the scientists have evaluated their latest techniques by comparing the model forecasts with a variety of existing observational datasets recorded at ARM sites and during several large-scale atmospheric field studies. The results show a significant advance in simulating real-world cloud and radiation interactions, according to Somerville.

"What we are starting on now is collaborative work to use our new cloud microphysical theories to try to improve the simulations of some of the world's leading climate models," Somerville said. "We also think we might be able to improve the accuracy of ordinary daily weather forecasts too, and that would be a worthwhile by-product of the climate research."

FUTURE STILL CLOUDY

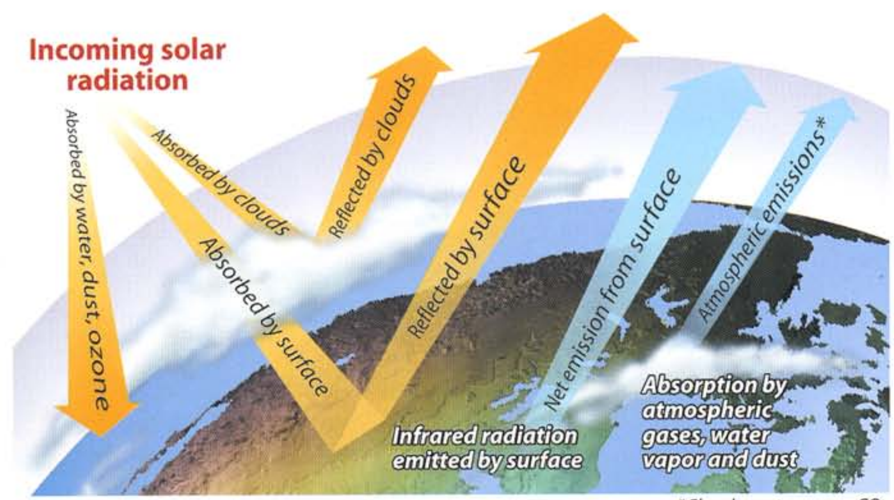
How stable the present cloud patterns are and how susceptible clouds may be to modification as the climate warms are still largely unknown. The net effect on clouds will depend on which cloud types change and whether they become more or less abundant, thicker or thinner, and higher or lower in altitude. As clouds change, how will the climate change?

"We're not sure what to expect. It could be positive or negative," Somerville said. "Clouds might alter so as to amplify a climate change, or they might act like a thermostat and reduce it. And the answer might be different in different places, different seasons, or different weather regimes."

Above, *Radiometers measure solar infrared radiation.*

The goal, then, is to continue improving climate models so that scientists can better understand what will happen as greenhouse gas amounts increase. Current models suggest that the doubling of atmospheric carbon dioxide concentration will eventually produce a global average surface warming of between 1.5 and 4.5 degrees Celsius (2.7 and 8.1 degrees Fahrenheit). This range is due to the use of different methods to represent cloud–radiation interactions in the leading GCMs.

"That is too great a range for policy makers to really have a good understanding of what may happen," Iacobellis said. "We want to reduce this uncertainty. By developing an improved understanding of how clouds and climate interact, we can contribute to creating the sound scientific basis that wise public policy requires."



*Clouds, water vapor, CO_2

Above, *The sunlight that reaches Earth drives the climate system. About 30 percent of solar radiation is reflected back into space, mainly by clouds. Infrared radiation emitted by the surface is also part of the outgoing energy. This complex exchange is known as Earth's energy budget.*

"THE PROBLEM IS TOO SMALL"

A Scripps researcher will use the world's most powerful computer to take an unprecedented look at climate in the United States throughout the past 50 years.

Over the next several years, starting in December, Masao Kanamitsu will employ Japan's Earth Simulator to process temperature, wind, moisture, surface-pressure, and precipitation data recorded by the National Weather Service. He'll crunch some 800 gigabytes of raw data. The output of the dynamical model will be 14 terabytes of data.

Despite the large amount of data in the tapes Kanamitsu will bear on his journey across the Pacific, the task will be a trifle to the Earth Simulator. The computer system opened in March 2002 in Yokohama, where a special building houses 5,120 CPUs working in unison to perform what's called "parallel vector computing," a method that allows the input and computation of several large numbers simul-taneously. On April 18, 2002, the center announced that in a demonstration, the Earth Simulator had performed at a peak of 35.61 trillion calculations per second, five times faster than the next-fastest supercomputer.

Kanamitsu spent several years at the National Weather Service reanalyzing data about the atmosphere from the 1940s to the present day using a special system designed for climate analysis. The reanalysis provided an invaluable source of data for a variety of researchers around the world; it has been cited in nearly 2,000 papers since the first reanalysis was published in 1996.

Reanalysis has proven valuable, but it does have limitations. One crucial drawback is its coarse horizontal resolution, which makes it difficult to use it for regional studies that require high spatial detail. The Earth Simulator, however, will enable Kanamitsu to perform a reanalysis of climate trends at a scale 10 to 20 times more detailed than what other computers could feasibly process.

Most computers that produce dynamical climate models present images of the atmosphere in 200-kilometer (124-mile) grids. The supercomputer, however, can present the evolution of climate in large regions over long periods of time at scales down to 10-kilometer (6-mile) grids. The difference is like the graphics of a modern computer game compared with those of decades-old prototypes like Pong. At the finer scale, what would look like formless blobs of rainy areas, for example, are transformed into distinct lines of storms along cold fronts.

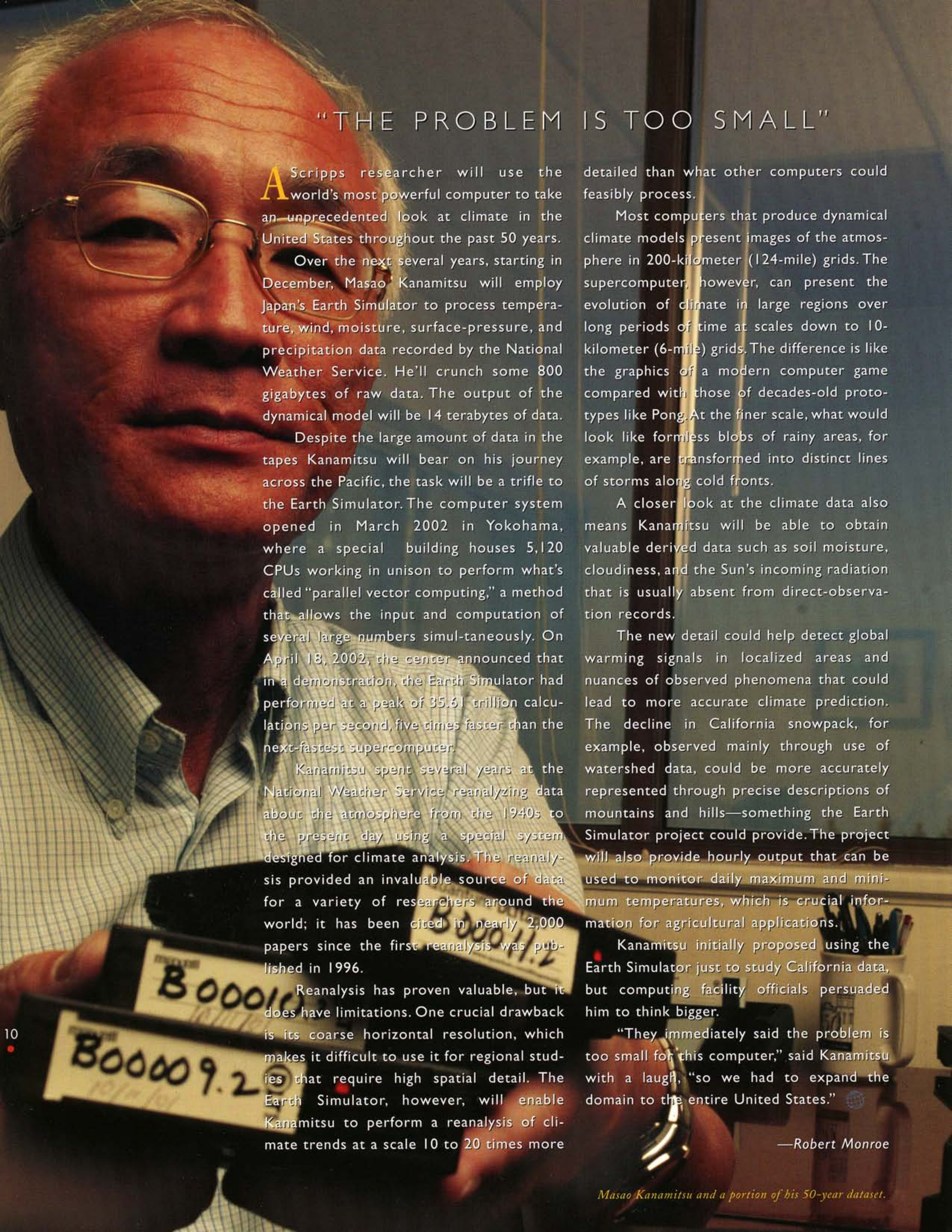
A closer look at the climate data also means Kanamitsu will be able to obtain valuable derived data such as soil moisture, cloudiness, and the Sun's incoming radiation that is usually absent from direct-observation records.

The new detail could help detect global warming signals in localized areas and nuances of observed phenomena that could lead to more accurate climate prediction. The decline in California snowpack, for example, observed mainly through use of watershed data, could be more accurately represented through precise descriptions of mountains and hills—something the Earth Simulator project could provide. The project will also provide hourly output that can be used to monitor daily maximum and minimum temperatures, which is crucial information for agricultural applications.

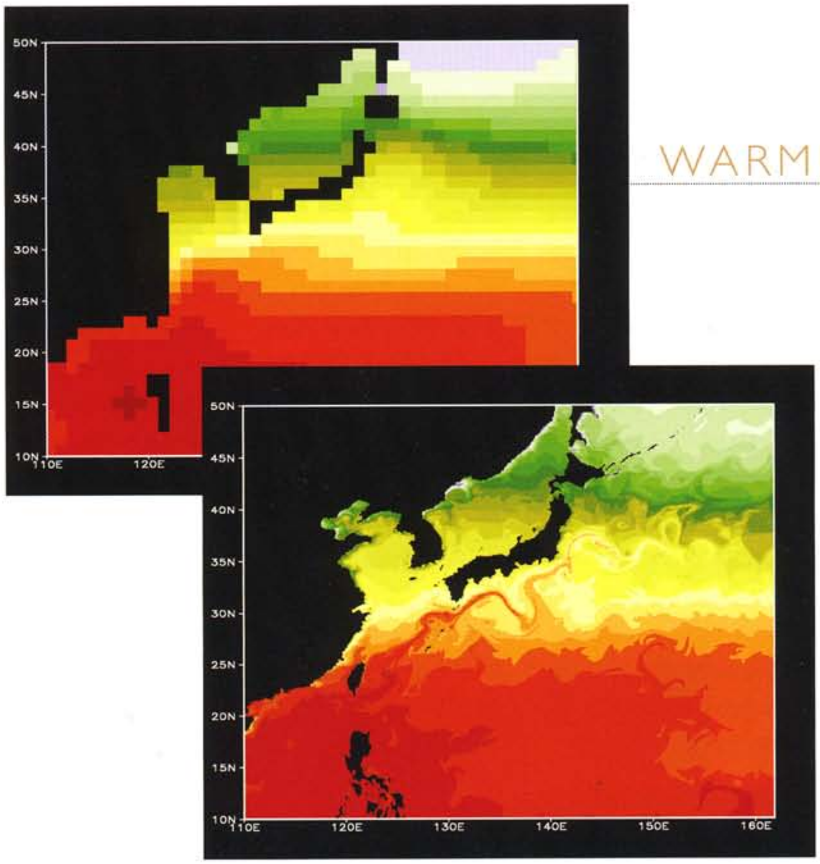
Kanamitsu initially proposed using the Earth Simulator just to study California data, but computing facility officials persuaded him to think bigger.

"They immediately said the problem is too small for this computer," said Kanamitsu with a laugh, "so we had to expand the domain to the entire United States."

—Robert Monroe



Masao Kanamitsu and a portion of his 50-year dataset.



Above, *In contrast with a 100-kilometer (62-mile) grid sea-surface temperature simulation (top), the eddies and jets of the Sea of Japan come to life in a 2002 Earth Simulator model able to resolve climate in 10-kilometer (6-mile) grids.*

WARMING UP TO A NEW DIET

What's killing off Alaska's Steller sea lions? The answer, it seems, is blowing in the wind. Numbers of the marine mammals have dropped by 80 percent since the mid-1970s. Despite a spectrum of culprits ranging from killer whale predation to overfishing to pollution, a major climate shift that began in 1976 is becoming the chief suspect.

The sea lions' decline appears to be but one ecological echo of the shift, in which cold waters of the northeastern Pacific Ocean began warming up in a reversal of the Pacific decadal oscillation. Scripps oceanographer Art Miller said that a chain of events, starting with a wind-whipped northward movement of currents and a subsequent displacement of eddies, has changed the northeastern Pacific food web.

"If a change in mesoscale eddy statistics occurred after the shift, such that eddies were more energetic in a different region of the Gulf of Alaska, then it suggests that the ecosystem itself was fundamentally altered," Miller said.

In ways scientists couldn't understand at the time, what happened in the mid-1970s set the Pacific Ocean on a course that would create profound changes. While the sea lions started to die off, sardine landings off California began to stabilize after decades of free fall, a trend likely started by the previous phase reversal in the 1940s. After 1975, the driest year in a half century, the city of Los Angeles experienced a progression of increasingly wet years that culminated in one of the strongest El Niño episodes of the century in 1982.

There is a dearth of essential ocean data prior to the shift, which Miller is hoping to make up for through use of a dynamical model that utilizes sea-surface temperature, salinity, currents, and sea level as variables in a reconstruction of events.

Ocean currents are prone to become unstable and form mesoscale eddies, strong swirls measuring as much as 100 kilometers (62 miles) across, whose churn stokes the increase of nutrients at the base of the food web. Eighteen months into the study, Miller and colleagues now believe that the strong Alaska Stream current intensified in the northern gulf in the mid-1970s. Because of the unstable stream and eddies, the primary production suddenly moved out of the range of sea lion haunts like Kodiak Island, leaving a new set of conditions that led to the dominance of different marine life. Lean pollock replaced fatty, more nutritious herring as the most common prey available to the sea lions—the so-called "junk food" of the sea lions' changed diet. These factors have diminished the pinnipeds' ability to survive and reproduce.

"If you grow a certain type of phytoplankton, a certain type of zooplankton can feed on that and it can work its way up the food web through a certain path that allows either herring or pollock to survive, depending on the organisms in between," Miller said. "There's very little information about what the ecosystem consisted of, so we're going to be using models again to try to sort this out."

—*Robert Monroe*

WARNING: TRAIN WRECK AHEAD

Imagine a future in which California receives half as much snow and has twice as many wildfires every year as it does now. Then envision an annual spawning cycle of salmon in the Northwest cut short by weeks, jeopardizing the survival of several species.

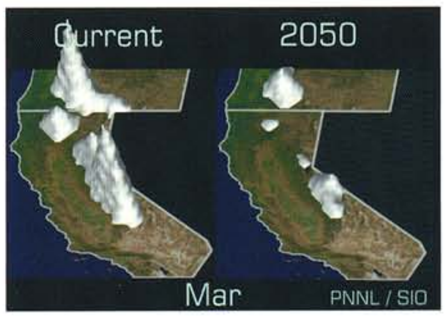
These visions are not doomsday scenarios but rather are forecasts of a recent project organized to understand the likely effects of greenhouse warming on the water supply of the western United States. The Scripps-led pilot project known as the Accelerated Climate Prediction Initiative (ACPI) involved the work of scientists from eight universities and federal research centers, who downscaled a global-scale, ocean–atmosphere climate model to specific regions of the West, illustrating what scenarios could occur in the next 100 years.

The results of the two-year-long initiative will be featured in a special upcoming issue of the journal *Climatic Change*. Component reports include projections that inland northern California waters will become increasingly salty, from the San Francisco Bay into the Central Valley. Other studies double the likelihood that Los Angeles will face a water-supply crisis by 2040.

The gravity of the ACPI results is underscored by the fact that it represents what many scientists consider an extremely conservative estimate of the West's future. Of the numerous climate models in use by scientists today, the Department of Energy (DOE)/National Center for Atmospheric Research (NCAR) Parallel Climate Model that was used in this project returns the smallest increases of climate warming for a given increase in atmospheric greenhouse gas concentrations.

"There's a range of estimates of global warming from different global models and the one we use is perhaps the least sensitive of all," said Scripps climate scientist David Pierce. "So these results are, if anything, a best-case estimate. It could be much worse."

The conservative basis of the initiative's methodology makes it less vulnerable to attack from camps within the global climate change debate. Among most scientists in the arena, the discussion over anthropogenic forcing is not whether it has caused the planet to warm but to what degree. The principal results that the DOE/NCAR model produced for ACPI were driven by air-temperature increases



Above, *Ski forecast for 2050: Poor conditions in the West.*
Opposite, top, *Salmon face an uphill struggle.*

and not by less-understood changes in precipitation that increase other models' margins of error. This makes the physics responsible for the dire predictions particularly solid.

The scientists incorporated comprehensive ocean temperature, salinity, and other physical data that had never been available before into their initial assessment of the current state of the climate system, further bolstering the forecast's credibility. These observations, taken over a five-year period from groundbreaking global-scale projects like the World Ocean Circulation Experiment, became the baseline for the model's climate change scenarios. Previous studies had relied on best-guess estimates of deep-ocean physical properties over long periods of time.

Human activities producing greenhouse emissions that force climate were also included as a variable to the model. The anthropogenic-forcing scenario assumed a "business-as-usual" estimate of future activity: worldwide economic growth and use of fossil fuels would continue to increase along observed trends. The model made no assumptions about possible effects of major mitigations of greenhouse gas emissions. Nor did it consider increases in population over the next several decades and the accompanying surge in demand for water and power. The result is a predicted general warming trend over the West of 1.0 to 1.6 degrees Celsius (1.8 to 2.9 degrees Fahrenheit) by mid-century.

The ACPI team then downscaled the global model to provide accounts of what kinds of impacts would take place at regional levels. In considering water-resource scenarios, the researchers focused on river systems in the West.

These localized estimates, which may represent best-case scenarios, suggest a future of seemingly insurmountable burdens placed on agriculture and city water supplies as well as on the environment. Most fundamentally, the researchers predict that the West will receive more precipitation as rain and not as snow—a simple result of the warmer temperature. Retreating snowpack and earlier spring flooding in most rivers have already been documented to the alarm of public agencies.

The shift in how the West gets its water does not bode well. The snowpacked mountains of the West act as a natural reserve of water, providing western states with water in the summer. Historically, snowmelt has meted out that supply in manageable fashion, aided by reservoirs that dot the bases of mountain ranges like the Sierra Nevada.

When wintertime precipitation comes in the form of rain instead of snow, however, reservoir managers are forced to release it or risk incurring damaging floods. The water supply that states need

in the spring and summer is given up to the Pacific Ocean in winter, having provided no benefit, said Pierce, whose ACPI study projects major changes in marine ecosystems as areas of primary nutrient production shift northward during the warming trend.

In addition, there are a number of secondary adverse effects that would be caused by the precipitation change. The temperature of river water provides cues for the reproductive cycles of salmon. Adults swim upstream to spawn in the coolness of fall; the young return to the sea when they feel the first rush of snow meltwater in the spring. ACPI member Lance Vail of the Pacific Northwest National Laboratory charted the disruptions at both ends of the spawning cycle that the switch from snow to rain would cause. The ACPI team concluded that the loss of certain species is likely regardless of any change in water-management policy.

After combining the model's forecast with his own statistical model, which considers vegetation availability as fire fuel and summer temperatures, Scripps scientist Anthony Westerling concluded that the West could experience twice as many wildfires in 100 years as it does now.

A University of Washington team led by researchers Niklas Christensen and Dennis Lettenmaier found that water levels in reservoirs fed by the Colorado River will diminish by one-third by mid-century. Hydropower generation could be cut by 40 percent. The diminished supply will severely curtail Los Angeles's ability to meet its water-supply needs and the ability of the federal government to live up to its treaty obligation to release prescribed amounts of Colorado River water flow to Mexico.

This all adds up to bad news for a system already at its limit, said Scripps climate scientist Tim Barnett, ACPI's coordinator and principal investigator.

"I don't think I've ever been in a project where there hasn't been some balance between bad news and good news," he said. "But in this case, there is no good news. We have to change the way our systems operate, even change our lifestyles, if we want to avoid the train wreck headed our way."

—*Robert Monroe*

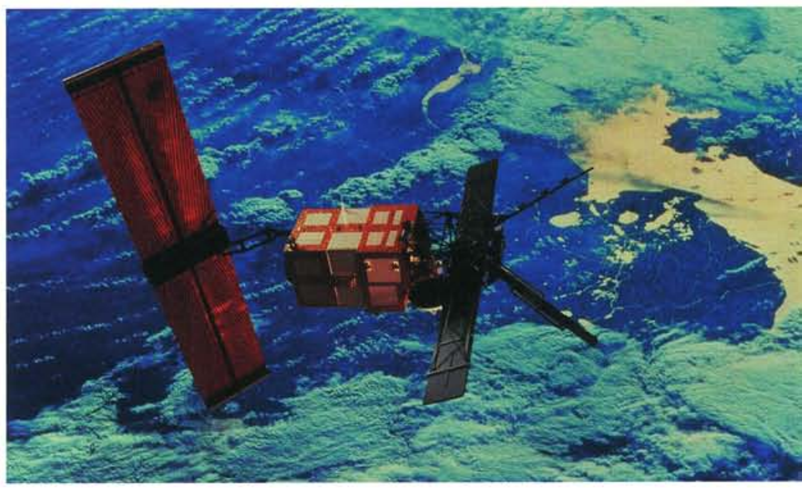
CLIMATE IS A TWO-WAY STREET

In the past, hydrologists and meteorologists viewed climate as a one-way action of the atmosphere imposed upon land. However, a new generation of high-resolution computer models is forcing researchers to see the bigger picture: that climate is the result of reciprocal interaction between land and sky.

The Experimental Climate Prediction Center (ECPC) at Scripps is working to improve land-surface models utilized by agencies like the National Center for Environmental Prediction. Researchers want to create forecast methodologies that better represent phenomena like snowpack and soil moisture. ECPC Director John Roads says that such variables have become more important as computerized representations of climate are being improved to scales as small as 10 square kilometers (3.9 square miles).

"Past models have had very simple interactions with the atmosphere and land," Roads said. "They haven't taken into account, for example, whether there's snow in a place or not."

For 22 years, Roads has seen computing power increase enough to provide forecasts that extend as much as seven months in advance and that can account for fine nuances once left to guesswork. Researchers can now model the role that moisture left in the soil after a rainy spring plays in influencing the heat of a summer day. Beyond precipitation, researchers hope to factor in vegetation anomalies, variations in the quantity and location of plant life, and the moisture it contains.



Above, *Land-surface models can "see" what weather satellites cannot.*

More accurate representations of such factors could ultimately aid an array of end users. Forest service officials are beginning to use ECPC's new models to estimate fire dangers in a given season. The farm industry seeks prediction schemes tailored to forecast crop productivity.

"One of the things these new models are going to help with is to let us really focus in on a particular region and start to understand individual characteristics rather than try to understand the whole global model at once," Roads said.

—*Robert Monroe*