Seeking Clues to Climate

Computer models provide insights to

Change

Earth's climate future.

THE air we breathe, the water we drink, the food we eat—climate affects them all. An atmospheric inversion holds down pollutants in a smoggy city, making it hard to breathe, until a change of weather brings a fresh breeze to blow it all away. A drought dries up water sources, and people and wildlife suffer until it rains and water flows freely again. Unseasonably hot or cold weather plays havoc with crops, ultimately affecting the price and availability of food for all.

Unusual weather patterns and rare strings of meteorological events occur naturally. A changing climate, however, can shift the odds enough so that humankind encounters unprecedented effects. And scientists now know that at least some aspects of Earth's climate are being altered by human activity. Data show that, over the past century, Earth has warmed measurably, and its atmosphere has changed.

At Livermore's Program for Climate Model Diagnosis and Intercomparison (PCMDI), Laboratory scientists are working with colleagues worldwide to better understand why the climate has changed and to improve predictions of the variations to expect in the future. (See the box on p. 6.) Comparing past data records with the results from climate models, PCMDI researchers are developing a clearer picture of the present and future patterns in the clouds above, the ground below, and the air all around.

Code Brings Clouds into Focus

One area of climate research directs the gaze upward, to the clouds. Modeling these masses of condensed water vapor is not straightforward. However, according to Livermore scientist Steve Klein, getting clouds "right" is vital to understanding what is in store for the future of Earth and its climate.

"Clouds modulate temperatures," says Klein. "Everyday experience shows us that cloudy days are cooler and cloudy nights are warmer than when skies are clear." During the daytime, clouds affect the transfer of solar radiation, preventing the Sun's radiative heat from reaching Earth's surface at full intensity. At night, clouds provide a "blanket" over Earth's surface, trapping thermal emission—the radiation emitted by a warmer ground—before it can escape into space. "These mechanisms are affected by sustained variations in climate and the increase in carbon dioxide in the atmosphere," says Klein. "But exactly how clouds will change is up for grabs at this point." Researchers want to determine, for example, whether a region will have more clouds or fewer and how reflective those formations will be.

Clouds also provide precipitation in the form of rain, snow, and ice. Plus they serve as the vehicles that transport water on the global "superhighway" of the atmosphere, with the rate of precipitation varying over time and geography. Some of this water makes its way into rivers, lakes, and groundwater and is used for drinking water and irrigation. "It's important to develop models that accurately predict the precipitation expected from clouds through climate change," says Klein.

Equally important is determining how accurately clouds are represented in climate models. One validation method is to re-create the past by running simulations with historical data and comparing the simulated cloud behavior with observations recorded by satellites since 1979. Much of the data collected for meteorological purposes is available through the International Satellite Cloud Climatology Project. A worldwide collaboration established in 1983, this project focuses on collecting and analyzing satellite radiance measurements to infer the global distribution of clouds; their properties; and their diurnal, seasonal, and interannual variations.

Satellite data come in different "flavors," depending on the types of sensors involved. Passive sensors measure what they "see" in the visible, infrared, and microwave portions of the spectrum. These sensors have limitations, however. For instance, they can provide information on the vertical level of the cloud top but not on a cloud's thickness, the altitude of its base, or the vertical distribution of condensate within it. "It is difficult for a passive sensor to distinguish between a cloud bank and snow on a mountain range," says Klein. "In terms of reflected light, both features look the same."

Active sensors, such as radar and lidar (light detection and ranging), emit signals

Program Addresses Climate Worldwide

The Program for Climate Model Diagnosis and Intercomparison (PCMDI) in Livermore's Physical and Life Sciences Directorate develops methods and tools for evaluating sophisticated climate models. Scientists worldwide rely on these models to project how rising concentrations of carbon dioxide and other factors will change the global climate. Established in 1989, PCMDI is funded primarily by the Regional and Global Climate Modeling Program and the Atmospheric System Research Program, both in the Climate and Environmental Sciences Division of the Department of Energy's Office of Science Biological and Environmental Research Program. PCMDI's mission is to assess climate models and reduce uncertainties in their predictions of future climate. Current activities include coordinating international model intercomparison studies, developing a model parameterization test bed, and devising rigorous statistical methods for detecting climate change and determining its causes.

Nearly two dozen Livermore scientists conduct PCMDI research in a wide range of areas. For example, they have made key contributions to the assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), which planners and policy makers use to prepare for and respond to future climate change. In recognition of its work to build and disseminate knowledge of human-induced climate change, IPCC shared the 2007 Nobel Peace Prize with former Vice President Al Gore.

In addition, PCMDI helped establish and now coordinates an ongoing international effort that facilitates the systematic evaluation of climate models and addresses the question of future climate change. During the third phase of this project, PCMDI and its partners enabled hundreds of researchers worldwide to subject models to unprecedented scrutiny and analysis. For its work, PCMDI was recognized by IPCC in its fourth assessment report, and the program received a special award from the American Meteorological Society.

Today, PCMDI scientists are helping to coordinate an even more ambitious follow-on project, phase five of the Coupled Model Intercomparison Project (CMIP5). CMIP5 calls for a set of coordinated climate model experiments agreed to by the modeling group representatives in the World Climate Research Programme's Working Group on Coupled Modelling. These experiments build on previous CMIP phases but include a more comprehensive set of simulations to enable model evaluation. The suite of simulations is designed to help researchers diagnose the processes responsible for differences in model projections of climate change and should allow them to better understand the uncertainty in the various projections. According to PCMDI director Karl Taylor, the results from CMIP5 will most likely provide the basis for much of the new climate science evaluated in the IPCC's fifth assessment report, planned for publication in late 2013.

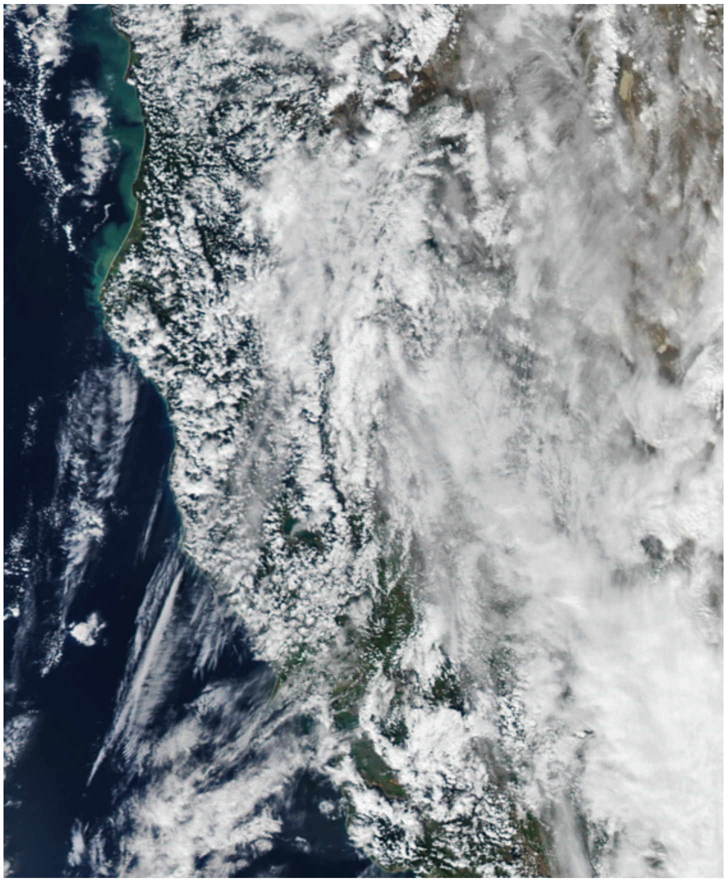
at wavelengths that penetrate clouds to varying degrees. Cloud characteristics determine the fraction of a pulse that is bounced back to the sensor and recorded. Active sensors can provide internal information, including the vertical distribution and density of condensed water inside a cloud mass. In addition, because each satellite has its own orbit, data recorded by different satellites can reveal how often clouds exist at particular points on the globe—the cloud cover, or cloud fraction, for a given region.

However, satellites do not directly measure many of the cloud quantities that interest climate scientists, such as the amount of condensate or the size of cloud particles. Instead, researchers must infer these properties through a retrieval algorithm, which converts observed measurements into the desired information.

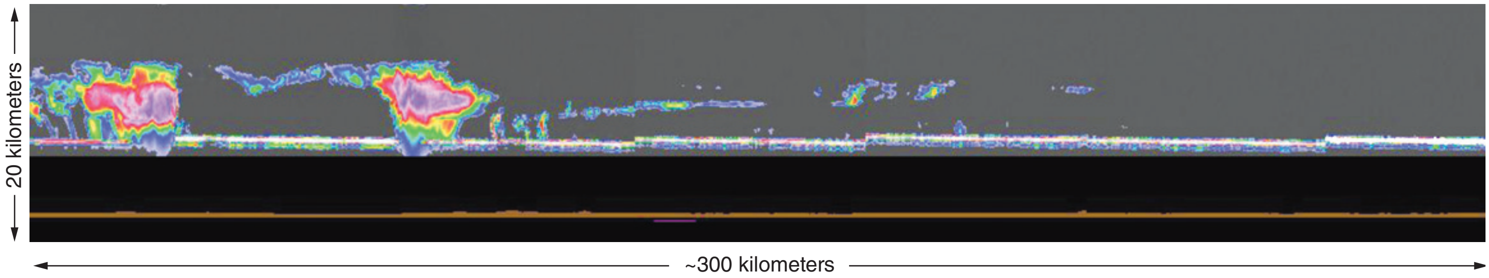
Furthermore, the definition of cloud types differs among observational platforms, and clouds detected by one sensor may not be found by another. A model might predict that clouds will exist at any atmospheric level where condensation occurs, but sensors may not detect a cloud that is overlapped by thick upper-level clouds. A comparison between modeled results and observed data thus requires a consistent definition of cloud types and diagnostic techniques that consider the effects of viewing geometry, sensor sensitivity, and vertical overlap of cloud layers.

To solve this problem, Klein and Livermore scientist Yuying Zhang are collaborating with researchers in Washington, Colorado, France, and the United Kingdom on the Cloud Feedback Model Intercomparison Project (CFMIP) to develop an integrated satellite simulator for use in climate models. The CFMIP Observation Simulator Package (COSP) is a diagnostic code that, when applied to the representation of clouds in a climate model, will emulate the data recorded by five satellites.

COSP mimics the observational process by converting model variables into pseudo-satellite observations. "It's designed to answer the question: What would a satellite see if the atmosphere had the clouds shown in a climate model?" says Klein. "If a model predicts a very thin cloud undetectable by a



Clouds are surprisingly difficult to simulate accurately in climate models.



This image, made from data recorded by the CloudSat satellite, shows the height and moisture content of two cumulus clouds. Colors indicate the amount of ice or liquid particles in the clouds, ranging from high (red) to low (blue).

satellite, for instance, we want the simulator to exclude that cloud from the comparison between model and satellite data. COSP should only count, or include, the model clouds that an actual satellite can record.”

By emulating the observational process, COSP allows researchers to compare modeled results with observational data and judge whether models are simulating clouds correctly. “If we want to improve our predictions of how clouds will change in the future,” says Klein, “we must accurately model the here and now as well as the patterns observed in the past.” Once a climate model can replicate satellite observations, scientists have more confidence in its ability to present an accurate picture of the future.

One area where COSP has been greatly improved is in its ability to deal with cloud resolution. Models and satellites differ in how well they resolve cloud details. Satellite observations typically have a horizontal resolution of about 1 kilometer, whereas models build simulations on coarser grids of about 100 kilometers. “Using a 1-kilometer grid to run global simulations of predicted climate patterns over the next 100 years would be prohibitively expensive in terms of computational time,” says Klein. “Working on such a fine scale is just not feasible. As a result, a satellite could easily detect small clouds that a simulation could not predict.”

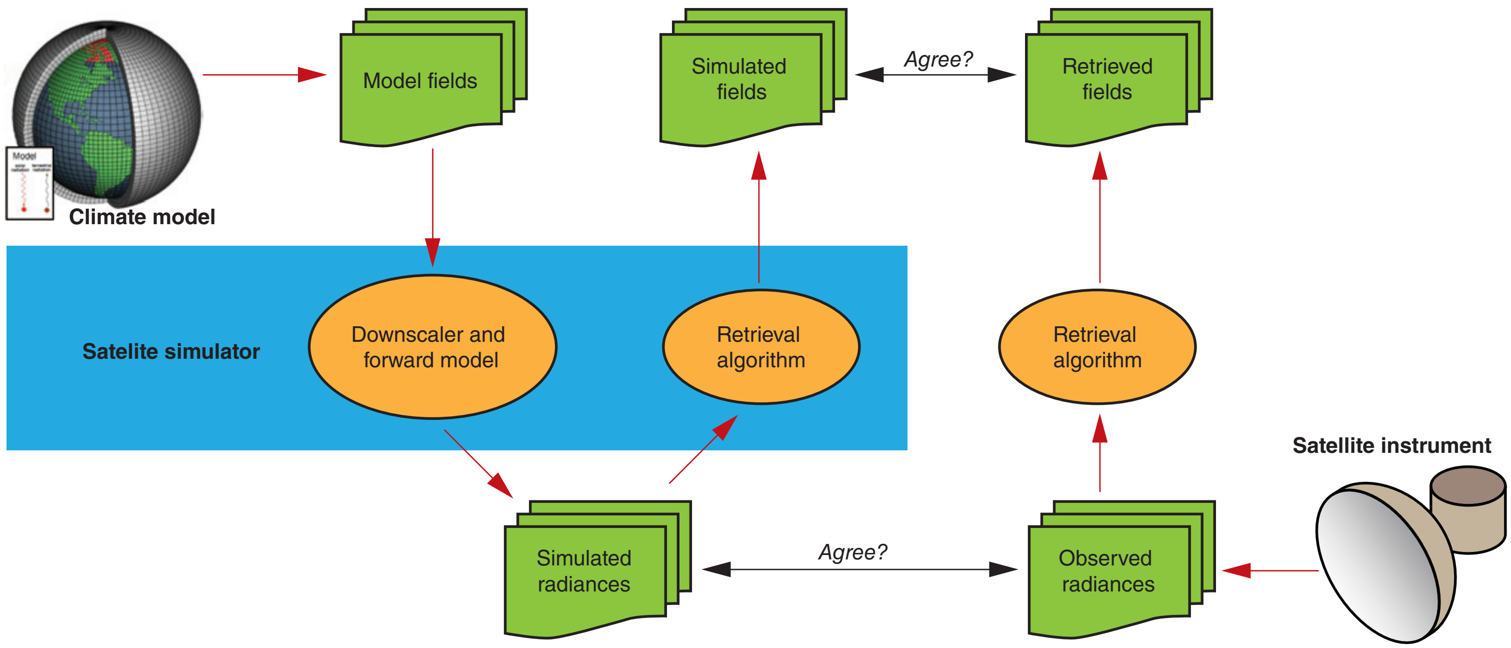
COSP addresses this issue by applying a technique known as downscaling to coarse resolutions. Zhang explains, “In a given simulation, COSP examines each 100-kilometer grid cell to see if that box contains clouds, and if so, what fraction of the box shows cloud cover. A grid cell with clouds is first divided into an equal number of vertical subcolumns. The model then assigns clouds to the columns in a manner consistent with the average amount of stratiform and convective clouds in that cell and with the model’s assumptions about cloud overlap.”

Next, an algorithm called SCOPS (subgrid cloud overlap profile samples) uses a pseudo-random sampling process to distribute cloud amounts into subcolumns. Zhang developed another algorithm, called PREC_SCOPS, to further distribute precipitation fluxes that are consistent with the distribution provided by SCOPS.

A measure of success in developing the satellite simulator is that most of the climate modeling centers worldwide have now incorporated the free code directly into their models to help scientists determine how accurately different models simulate clouds. The CFMIP team is also creating a standard for model output, so researchers can easily compare their results with those from other climate centers. In addition, the team continues to consolidate and refine COSP to reduce the computational time it consumes and make the code easier to use.

Looking at Regional-Scale Changes

Climate modeling on the global scale is one thing, but modeling the climate for one’s regional backyard is something else. At regional scales, the climate change signals are about the same size as those at the global scale, but the background “noise,” or natural variability,



To ensure that climate simulations accurately represent clouds, researchers at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) have developed a cloud simulator code called COSP. When incorporated into a climate model, COSP mimics the measurements recorded by satellites, allowing climate scientists to better compare simulated results with observed data.

is often much larger and may completely obscure the signal. Moreover, the local response can be strongly affected by local forcings—those natural or human-induced factors that affect climate—and these forcings are more uncertain at regional scales. Livermore climate scientist Celine Bonfils is leading several studies to investigate whether changes observed in different regions are caused by natural variation or by human activity.

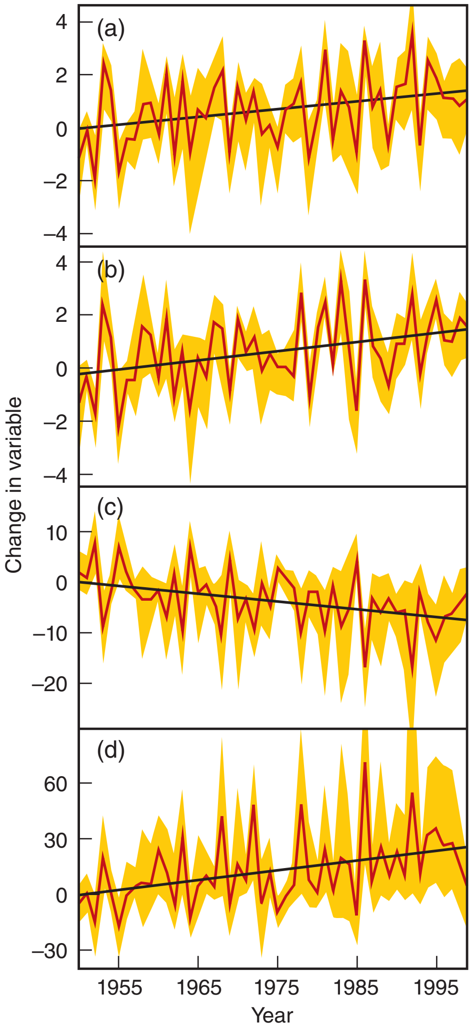
One project is exploring changes in western U.S. hydrology. Measurements show that since the mid-20th century, less snow and more rain are falling in the mountainous regions. In addition, snowpacks are smaller at low and mid elevations, and snowmelt seasons are beginning earlier. Regional warming looked to be the likely culprit, but the exact mechanisms of that warming had not been rigorously studied. Bonfils and colleagues from Lawrence Livermore, Scripps Institution of Oceanography, the U.S. Geological Survey, the University of Washington, and the National Institute for Environmental Studies in Japan conducted a regional detection and attribution study to identify signals that indicate the cause of an observed change. "We wanted to determine not only where the temperatures are changing over the mountainous regions of the western U.S.," says Bonfils, "but also whether those changes are due primarily to natural causes or are human induced."

Finding these signals involves searching past records for a pattern of climate change that has also been predicted by a computer model. Such a pattern could be due solely to natural changes—an increase in the Sun's energy output from a solar flare, for instance, or more volcanic ash in the air from a volcanic eruption—or it could be due to human influences, such as increases in the atmospheric levels of greenhouse gases. Each forcing mechanism has a distinctive signature, or fingerprint, in climate records. Fingerprint techniques allow researchers to examine a change in the climate system and then make rigorous statistical tests of possible explanations for that change. "Having a better understanding of the mechanism behind an observed warming allows us to make realistic projections about the future," says Bonfils. "Once a fingerprint is identified in the data from past records, we can have confidence in moving forward."

Answers are not easy to come by on regional scales. The climate of the western U.S., for example, is affected by strong natural variations, such as El Niño, La Niña, and the Pacific Decadal Oscillation, which in other regions have a smaller effect. In addition, the western U.S. is topographically complex, leading to small-scale climate features that global models may not adequately resolve. Plus, most model simulations often ignore local forcing mechanisms such as the changes associated with agriculture, urbanization, and irrigation. Together, these factors make it difficult to identify the regional manifestations of climate changes that are unambiguous at global scales.

For the fingerprint study, the team used four hydrologically relevant surface-temperature variables: the seasonal averages of daily minimum and maximum temperatures, the number of frost days, and the number of degree-days above 0°C (a variable that defines temperature-driven snowmelt). In the detection phase of the study, the researchers investigated whether the observed changes in the variables could be fully explained by natural internal climate variability. The attribution phase of the study focused on determining whether the observed changes were consistent with climate simulations that included anthropogenic effects such as greenhouse gases, ozone, and aerosols or only solar and volcanic forcings. Downscaling techniques were applied to transform data from three global models to smaller, regional scales.

The team's results indicate that the changes observed since 1950 are consistent with the climate response to anthropogenic forcing and outside the range expected from any natural internal climate variability. Models project an acceleration of warming, with temperatures



A PCMDI study of regional climate forcings examined four variables for nine mountainous regions in the western U.S.: (a) minimum temperature, (b) maximum temperature, (c) number of frost days, and (d) number of degree-days above 0°C for the months January through March. Red lines are results for each variable averaged over nine mountainous regions, all four of which predicted regional warming. Gold shading shows the range of minimum and maximum values for the nine regions. Black lines indicate the least-squares best-fit linear trend.

in California increasing between 1° and 3°C by 2050, and between 2° and 6°C by 2100—important information for decision makers charged with maintaining the region's water infrastructure and ensuring long-term sustainability for the state's water supply.

Warming in the Frozen North

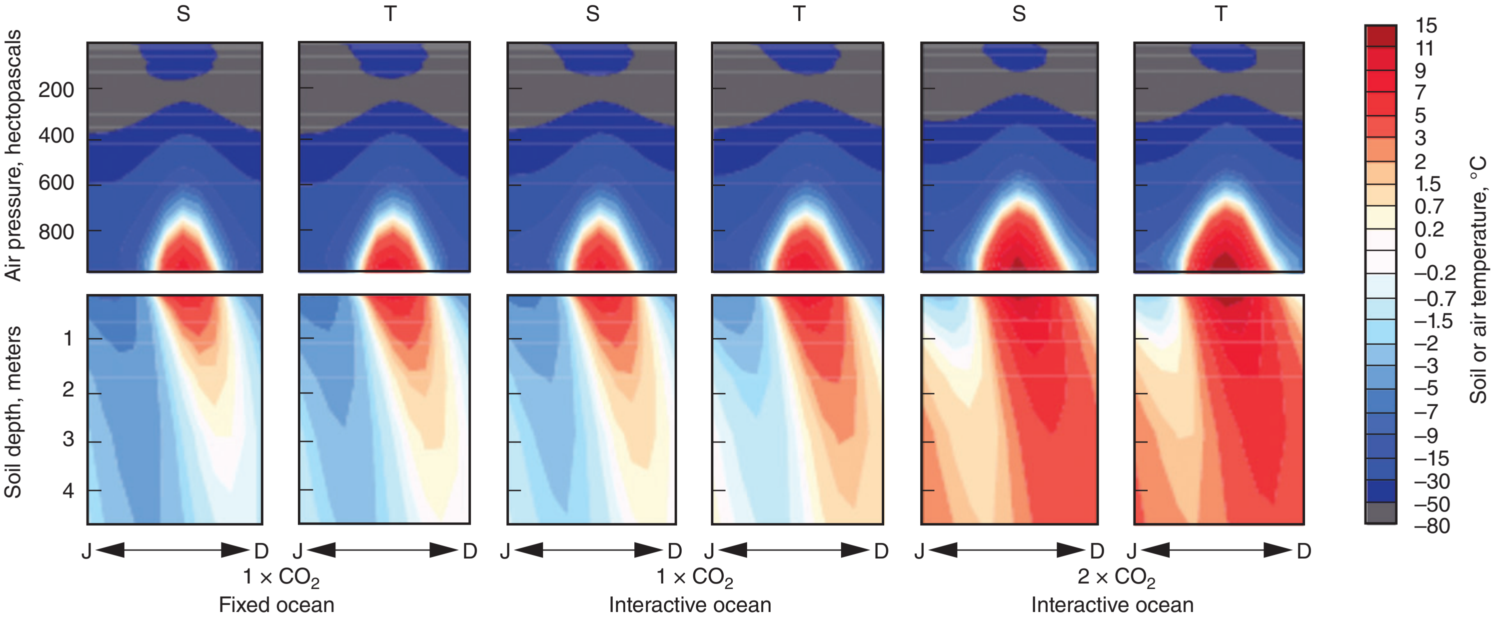
In another study, Bonfils examined a much less vegetated area of the world: the boreal region encircling the Arctic. Permafrost rules in this region, and vegetation consists mostly of short shrubs and tundra. But a warming climate is changing these features as well.

Most boreal studies have focused on what happens as vast areas of tundra convert to forests, a scenario not likely to occur in the 21st century because trees grow and conquer new grounds relatively slowly. However, tundra could convert to shrub-covered areas more quickly. Says Bonfils, "As climate warms and the growing season lengthens, shrub coverage would expand, and the shrubs would grow bigger and taller."

Bonfils is leading a collaboration with the National Center for Atmospheric Research, Lawrence Berkeley National Laboratory, the University of California at Berkeley, and PCMDI researchers to analyze the potential impact of a large-scale tundra-to-shrub conversion. Idealized experiments with the Community Climate System Model used three representations of the area's vegetation: the present-day distribution of short shrubs, a "greener" scenario in which short shrubs cover a wider area than they do now, and a third scenario in which tall shrub coverage expands, instead of short shrubs. Other land-cover types, including different vegetation, glaciers, wetlands, and lakes, were held constant so that the modeled effects came only from shrubs.

In simulations with increased shrub coverage, substantial atmospheric heating resulted from two seasonal land–atmosphere feedback mechanisms. Surface albedo, the fraction of solar energy reflected from Earth's surface, decreased, and the atmospheric moisture content from evapotranspiration increased. "These results show for the first time that the strength and timing of the two mechanisms greatly depend on shrub height and the time at which branches and leaves protrude from the snow," says Bonfils. Taller shrubs reduce the albedo earlier in the spring and transpire more efficiently than shorter shrubs, thereby increasing soil warming and destabilizing the permafrost more efficiently.

In a second part of the study, the team replaced bare ground with tall or short shrubs for three climate scenarios. The first scenario kept the ocean surface temperature unchanged, or fixed. The



In a PCMDI study of the Arctic boreal region, simulations compared the annual air and soil temperature as a function of height and depth in response to short (S) and tall (T) shrub invasions over a calendar year, January (J) to December (D). The model configurations included fixed ocean temperatures, an interactive ocean, and an interactive ocean plus double the amount of atmospheric carbon dioxide (CO_2). Results showed that the active layer thickness (or the thaw depth) deepens with the invasion of shrubs. This layer deepens even further when the ocean is active. The below-freezing season also shortens. When shrub expansion is paired with a warming ocean and increased atmospheric carbon dioxide, refreezing of the soil occurs only in the top meter. Below that, the soil no longer freezes, even in winter, and the heat content of the soil increases overall.

second simulation allowed the ocean and sea ice to interact with the atmosphere. In this scenario, additional warming occurs as sea ice melts. The reduced sea-ice cover lowers the surface albedo further and ocean evaporation increases, adding more water vapor to the atmosphere.

In the third simulation, researchers doubled the carbon dioxide in the atmosphere. This last scenario expanded an underground layer that freezes and thaws. Says Bonfils, "With shrubs in place, this active layer moves deeper, and more of the ground stays unfrozen year-round. Adding shrubs to the tundra landscape changes the activity above and below ground in a significant way."

Bonfils adds that the permafrost layer is a repository of methane, a greenhouse gas about 20 times more damaging than carbon dioxide. When areas that are frozen solid begin to thaw, they may release methane, which could lead to even more changes for the vulnerable, remote region. New simulations would be needed to test this hypothesis.

Different Models, Different Results?

Another concern for climate researchers and policy makers is whether the specific model chosen for a study affects the results. Most detection and attribution studies use a few climate models to produce a fingerprint template that is then matched to historical data. In a 2007 study, a PCMDI team led by climate scientist Ben Santer pooled results from 22 models to determine what caused changes in the atmosphere's moisture content. "We wanted to study the amount of water vapor the air holds because we have a lot of historical data showing how this characteristic has changed over time," says Santer. Routine, satellite-based measurements, which began in 1987, show that atmospheric moisture content has increased significantly.

The model data were taken from simulations performed in support of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC). "We relied on climate model output for estimates of the water-vapor fingerprint in response to human-caused changes in a variety of factors," explains Santer. "We also used the output for estimates of purely natural changes in climate—the background noise we need to take into account while trying to distinguish the fingerprint signal."

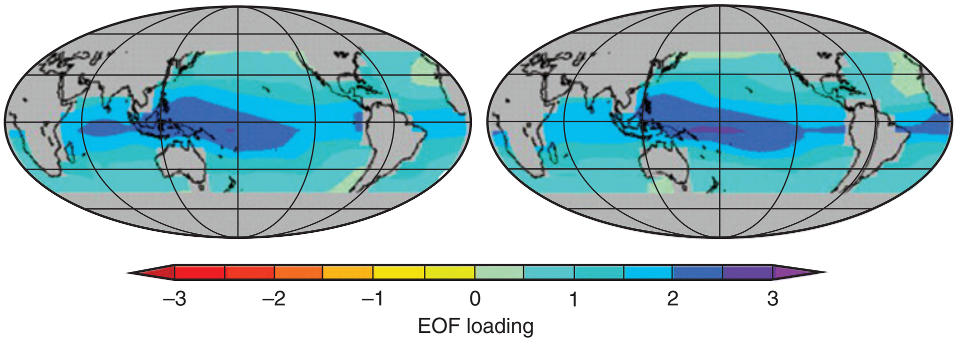
The simulated pattern of human-induced changes in water vapor produced by the 22 models correlated strongly with the data collected by satellites. The fingerprint for this increase was primarily due to the additional greenhouse gases added to the atmosphere by burning fossil fuels.

After these results were published, climate scientists asked whether the study would produce the same findings if, instead of 22 models, the team chose only the better climate models. "It was a reasonable question," says Santer, "so we attempted to identify the top 10 models of the 22 we originally used. We then tried to determine whether these better models showed the same human-caused fingerprint."

The team found that defining what factors makes one model "better" than another is not straightforward. "There isn't just one 'killer variable' that can foretell performance," says Santer. "Each model has strengths and weaknesses, depending on its focus, whether that is seasonal cycle, geographic region, or some other parameter. No single variable rules them all."

To rank the models, the team evaluated 70 performance metrics. One group of metrics examined how well a model captured important features of today's average climate. Another set focused on changes occurring over several seasons in the present-day climate. The largest set provided information on a model's skill in simulating the size and geographic patterns of observed climate variability. "We looked at this variability on different timescales—from month to month, year to year, and decade to decade," says Santer.

The team calculated the metrics for two climate variables, water vapor and sea-surface temperature, over several regions. "We found little relationship between a model's performance in portraying the mean state of these variables and the metrics," says Santer. The researchers then explored the sensitivity of fingerprint results to the procedures chosen for ranking the models. They used the six approaches to identify the 10 best and worst models and then repeated the fingerprint analysis many times.



To determine whether model quality affects simulated results, PCMDI researchers compared fingerprints produced by the top 10 models (left) with those produced by the bottom 10 (right). Fingerprints are based on an empirical orthogonal functions (EOF) analysis, which represents the weight of the signature at each grid point. The fingerprints show distinctive evidence of externally forced changes in water vapor over near-global ocean bands—simulated oceans that exclude areas where observational data and, thus, simulated results are less reliable.

Results indicated that a model's quality had little influence on its ability to identify a human fingerprint in satellite records of water vapor changes. No matter which models were used—the best or the worst—the fingerprint of human impact remained. "It's not terribly surprising because the increase in water vapor is very straightforward physics," says Santer. A warmer ocean surface leads to warmer air above the ocean. Warmer air holds more water, as visitors to a tropical location quickly discover. In addition, the patterns of natural water vapor fluctuation differ significantly from the signature imposed by human effects.

"The human effects lead to a steady overall increase in the amount of water vapor in the atmosphere," says Santer. "The entire panoply of the changing climate shows internal consistency. When we look at the story—the changes in water vapor and ocean temperature—it's like a well-constructed novel with no plot holes or unresolved character issues. In the end, the story does, indeed, make sense."

Looking to the Future

Climate research at the Laboratory continues, with efforts to "pin down" clouds in simulations, explore what changing climates mean on regional levels, and determine the quality of models for various fingerprinting activities. And as humanity searches for what these variations will mean for current and future generations, the Laboratory does its part to help present a more accurate picture of the future climate.

"We bring the best science we can to the challenge of climate science," says PCMDI director Karl Taylor. "The more information we have about the expected future and the more certain we are that that information is accurate, the better off everyone is." Improving scientific understanding of the uncertainty and the consequences of climate warming under various scenarios will help policy makers form an action plan for mitigating the effects and helping humankind adapt to the new environment.

—Ann Parker

Key Words: boreal, climate change, CFMIP Observation Simulator Package (COSP), Cloud Feedback Model Intercomparison Project (CFMIP), cloud simulation, fingerprinting, global warming, permafrost, Program for Climate Model Diagnosis and Intercomparison (PCMDI), regional climate modeling.

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