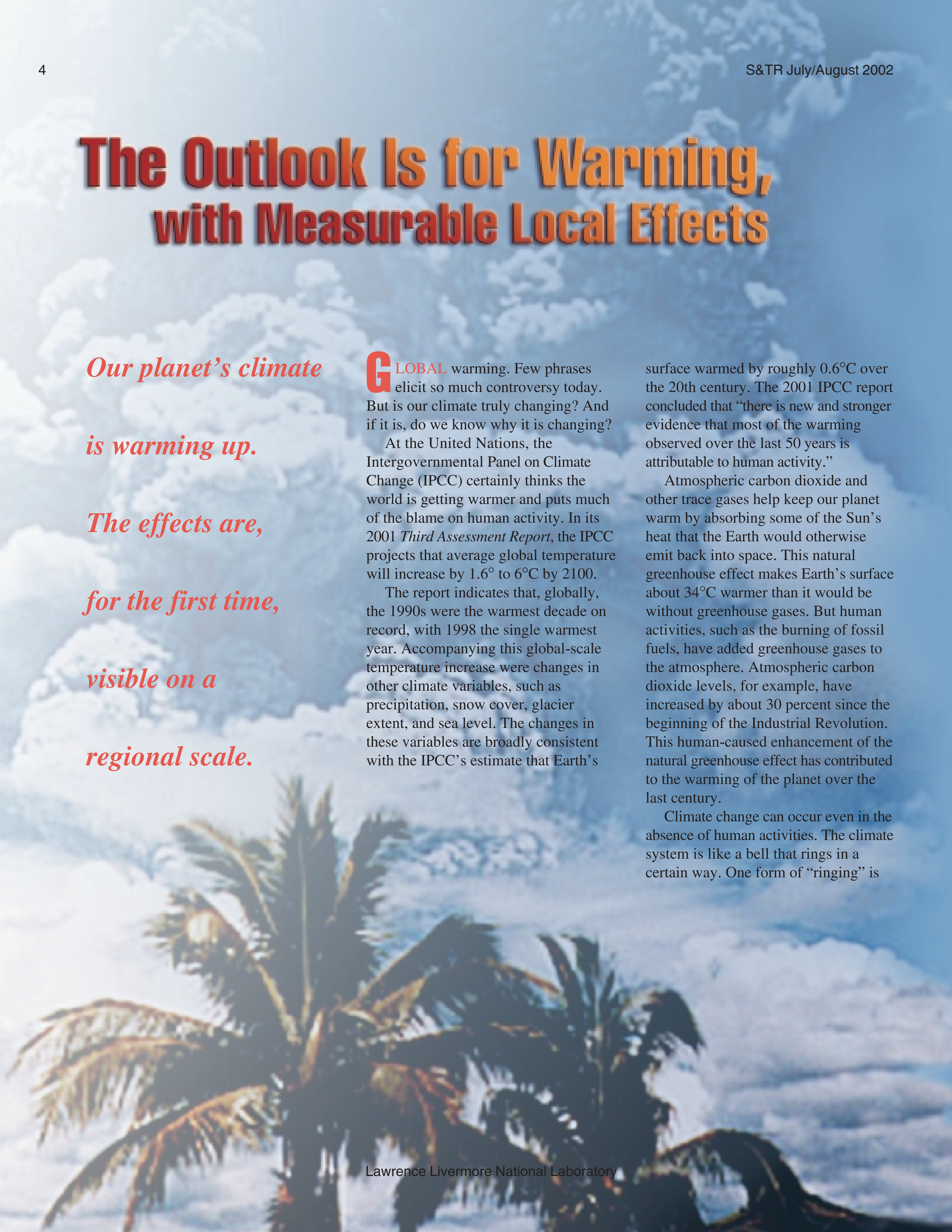


The Outlook Is for Warming, with Measurable Local Effects

Our planet's climate is warming up. The effects are, for the first time, visible on a regional scale.

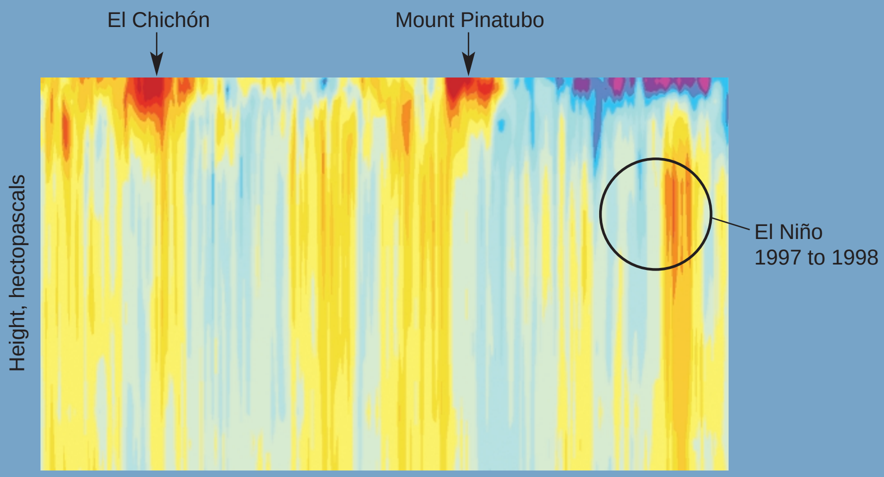
GLOBAL warming. Few phrases elicit so much controversy today. But is our climate truly changing? And if it is, do we know why it is changing?

At the United Nations, the Intergovernmental Panel on Climate Change (IPCC) certainly thinks the world is getting warmer and puts much of the blame on human activity. In its 2001 *Third Assessment Report*, the IPCC projects that average global temperature will increase by 1.6° to 6°C by 2100.

The report indicates that, globally, the 1990s were the warmest decade on record, with 1998 the single warmest year. Accompanying this global-scale temperature increase were changes in other climate variables, such as precipitation, snow cover, glacier extent, and sea level. The changes in these variables are broadly consistent with the IPCC's estimate that Earth's surface warmed by roughly 0.6°C over the 20th century. The 2001 IPCC report concluded that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activity."

Atmospheric carbon dioxide and other trace gases help keep our planet warm by absorbing some of the Sun's heat that the Earth would otherwise emit back into space. This natural greenhouse effect makes Earth's surface about 34°C warmer than it would be without greenhouse gases. But human activities, such as the burning of fossil fuels, have added greenhouse gases to the atmosphere. Atmospheric carbon dioxide levels, for example, have increased by about 30 percent since the beginning of the Industrial Revolution. This human-caused enhancement of the natural greenhouse effect has contributed to the warming of the planet over the last century.

Climate change can occur even in the absence of human activities. The climate system is like a bell that rings in a certain way. One form of "ringing" is



Globally averaged temperatures have changed at different levels in Earth's atmosphere. This profile is from close to Earth's surface through to the stratosphere. Temperatures are in the form of departures (anomalies) from long-term monthly means computed from 1979 to 1999 and are in degrees Celsius. The stratospheric warming caused by the El Chichón and Mount Pinatubo volcanic eruptions is clearly evident, as is the cooling of the lower atmosphere after Pinatubo. Results are from the so-called reanalysis project jointly performed by the National Center for Environmental Prediction and the National Center for Atmospheric Research.

the ocean warming phenomenon known as El Niño or its cooling sister, La Niña. Such changes are thought to be due to the internal variability of the climate system. But external events can also cause natural climate changes. Large volcanic eruptions can pump massive quantities of dust into the upper atmosphere (the stratosphere). The dust may remain in the stratosphere for years, cooling Earth's surface by absorbing and reflecting some of the incoming sunlight. Natural changes in the Sun's energy output and slow changes in Earth's orbit can also influence climate.

Carbon dioxide and other greenhouse gases get the most press, but there are other human influences as well. Changes in land use can be a concern. For example, Livermore scientists recently showed that human-caused changes in land-use patterns (especially conversion of forests to farm land) may have caused a gradual global cooling of approximately 0.25°C, mostly before the 20th century.

Large-scale burning of rain forests sends particulate matter into the lower atmosphere, warming us. At the same time, with fewer trees, less carbon dioxide can be absorbed from the atmosphere, which warms us further. Land surface changes also affect Earth's reflectivity, or albedo.

If Earth is getting warmer, is it possible to expose individual factors causing climate change? And what will global warming mean on a regional level? Two Livermore research teams are searching for—and finding—answers.

Atmospheric scientist Ben Santer, a 1998 John A. and Catherine T. MacArthur Foundation Fellow, has used sophisticated climate models to separate the effects of recent major volcanic eruptions and El Niños from other causes of climate change. The motivation for this research was to shed light on one of the outstanding puzzles in climate science: why Earth's surface has apparently warmed faster than the lower atmosphere.

At the same time, a team led by physicist Philip Duffy has brought the highest resolution yet to global climate modeling, revealing a wealth of regional effects for the first time. Instead of a 300-kilometer grid—the previous state of the art—Duffy's team has been able to perform global simulations using models with grid cell sizes of 75 and even 50 kilometers. These are the finest-resolution global climate simulations performed to date. The figure on p. 6 compares these resolutions.

Duffy's work would not be possible without Livermore's massively parallel supercomputers, which can quickly perform the computationally demanding calculations inherent in global climate modeling. The first simulations using the 50-kilometer grid ran on the Advanced Simulation and Computing (ASCI) White computer during its initial, unclassified testing period in December 2000. Because the ASCI White computer is now used exclusively for classified computations, models used by Duffy's group are being run on other supercomputers at Livermore and at Lawrence Berkeley National Laboratory.

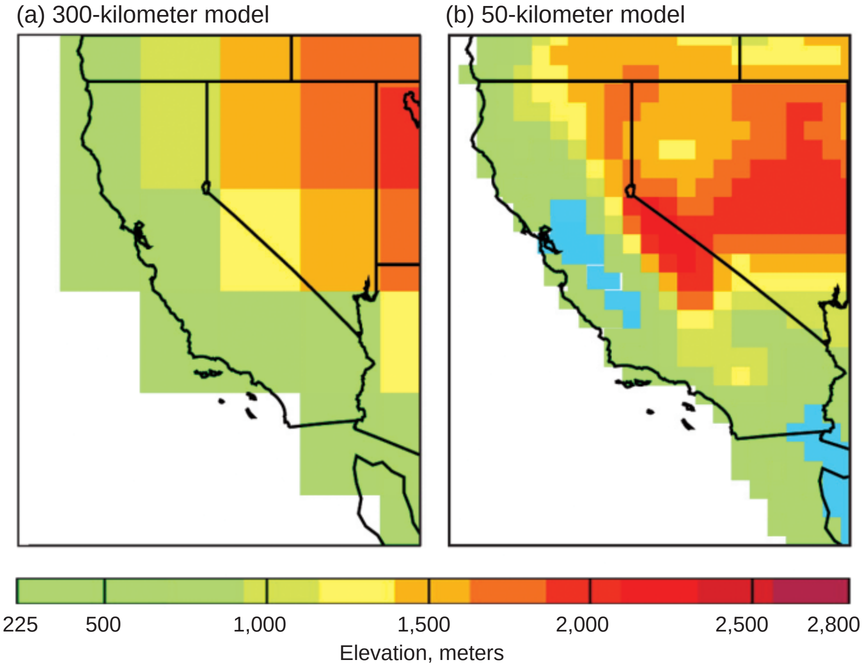
A 1-year simulation of global climate using the 300-kilometer grid can now be accomplished in 4 or 5 hours. Five years ago, it would have taken over a day to complete a comparable simulation. For the 50-kilometer grid, “At best, we can do about a month of simulated climate in a day,” says Duffy. A 50-kilometer grid for climate modeling was the stuff of dreams 5 years ago.

Why the Controversy?

Much of the controversy about global warming results from two apparent contradictions. One relates to observed temperature data and the other to the issue of how well computer models of the global climate system can represent such observations.

While Earth’s surface has warmed by about 0.15° to 0.2°C per decade since 1979, temperatures in the troposphere (the layer of the atmosphere extending from Earth’s surface to 8 to 16 kilometers above it) have shown little warming, and even a slight cooling.

The apparent lack of tropospheric warming from 1979 to the present has been used to cast doubt on the reality of strong surface warming. It is important to understand whether this difference between surface and tropospheric warming rates is real or is an artifact of data problems. If this difference is real, what factors might be causing it?



The topography of California and Nevada is simulated in models with (a) 300-kilometer and (b) 50-kilometer grids. Models that use the 300-kilometer grid have been the state of the art, but Livermore has developed a 50-kilometer-grid model. Even with 50-kilometer grids, the topography of California and Nevada is not represented. The Coast Range mountains are not visible in (b), and the data smoothing process lowers the elevation of the Sierra Nevada mountains.

The second puzzle relates to the inability of many climate models to simulate the apparent difference in surface and tropospheric warming rates. This inconsistency is sometimes used to bolster arguments that models are inappropriate tools for making projections of future climate change.

Recent work by Santer and his colleagues has addressed both of these puzzles. They have learned that at least some of the differential warming of Earth’s surface and lower troposphere is real and attributable to the combined effects of stratospheric ozone depletion, volcanic eruptions, and natural climate variability. Differences in the geographic regions sampled by the surface thermometer network and the satellite-based tropospheric temperature measurements also explain some of the divergent temperature changes of the surface and troposphere.

“But,” Santer concedes, “accounting for these effects still does not fully explain the different rates of temperature change. Nor does it explain why models don’t reproduce this differential behavior accurately.”

A Search for Resolution

For several years, Santer has been working with other investigators at Livermore and research institutions around the world to reconcile the apparent contradictions in actual data and global climate models. In one study of climate between 1979 and 1998, they discovered that a model including anthropogenic (human-caused) factors and volcanic aerosols produced surface–troposphere temperature differences that were the closest yet to actual observed data.

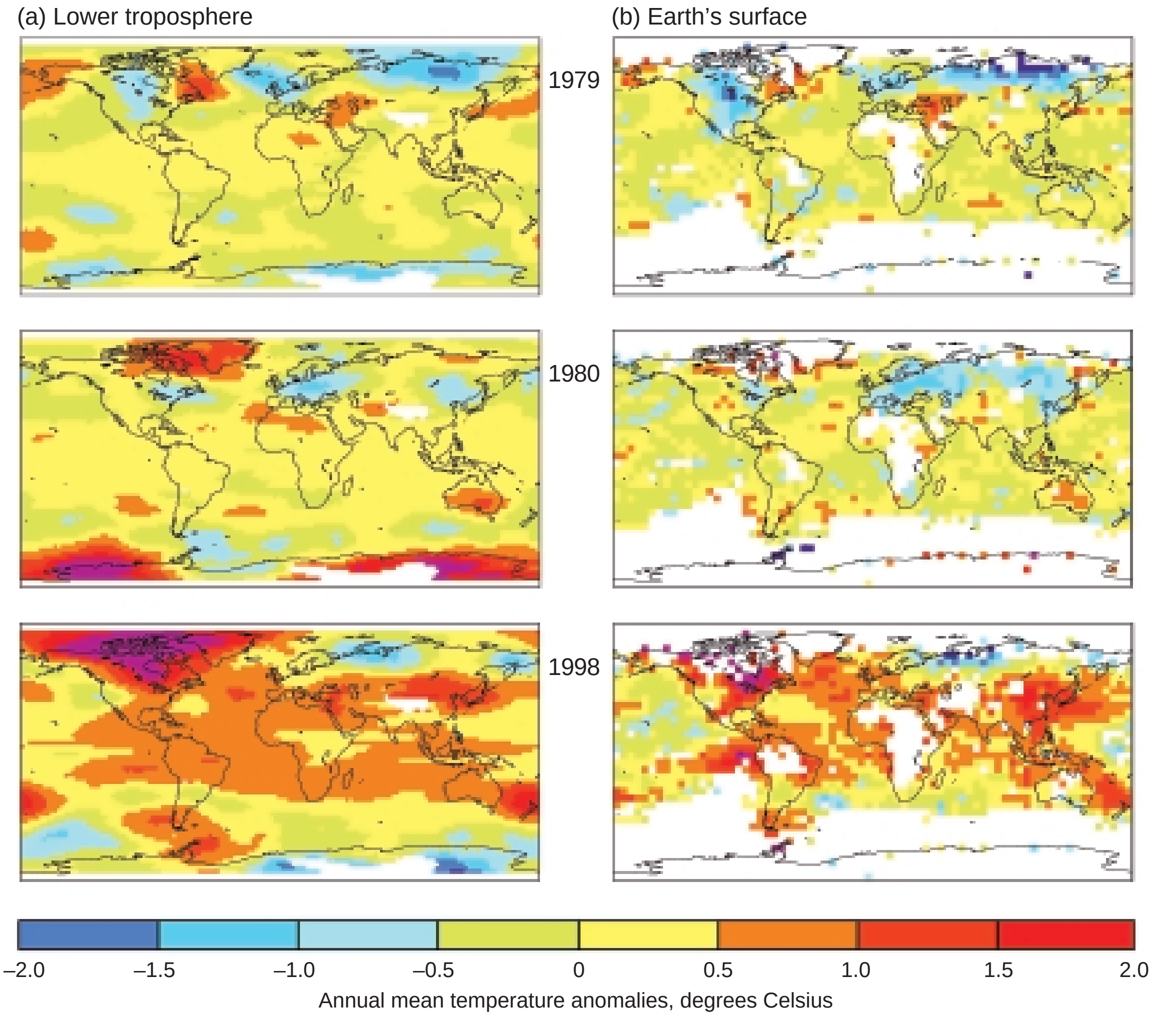
As a follow-up, they wanted to examine the influence of volcanoes alone. But, says Santer, “We had a bit of bad luck. Nature made our lives difficult. There was a major El Niño in

1982, at the same time as the eruption of El Chichón in Mexico. A smaller El Niño coincided with the 1991 eruption of Mount Pinatubo in the Philippines. This made it tough to disentangle the effects that volcanoes and El Niños had on surface and tropospheric temperatures."

Santer and his Livermore colleagues had been doing similar work for the past 10 years. For the first half of that time, they were trying to identify human-caused climate signals in observed temperature records. This involved using both model and observational climate data to understand the characteristic fingerprints of the many natural and anthropogenic influences on climate. (See the figure on p. 8.)

Previous researchers had attempted to remove the effects of explosive volcanic eruptions and El Niños from surface and tropospheric temperatures so they could obtain better estimates of the underlying human component of climate change. But Santer's team was the first to deal fully with the correlation of volcanic eruptions and El Niños, known in statistical problems as collinearity.

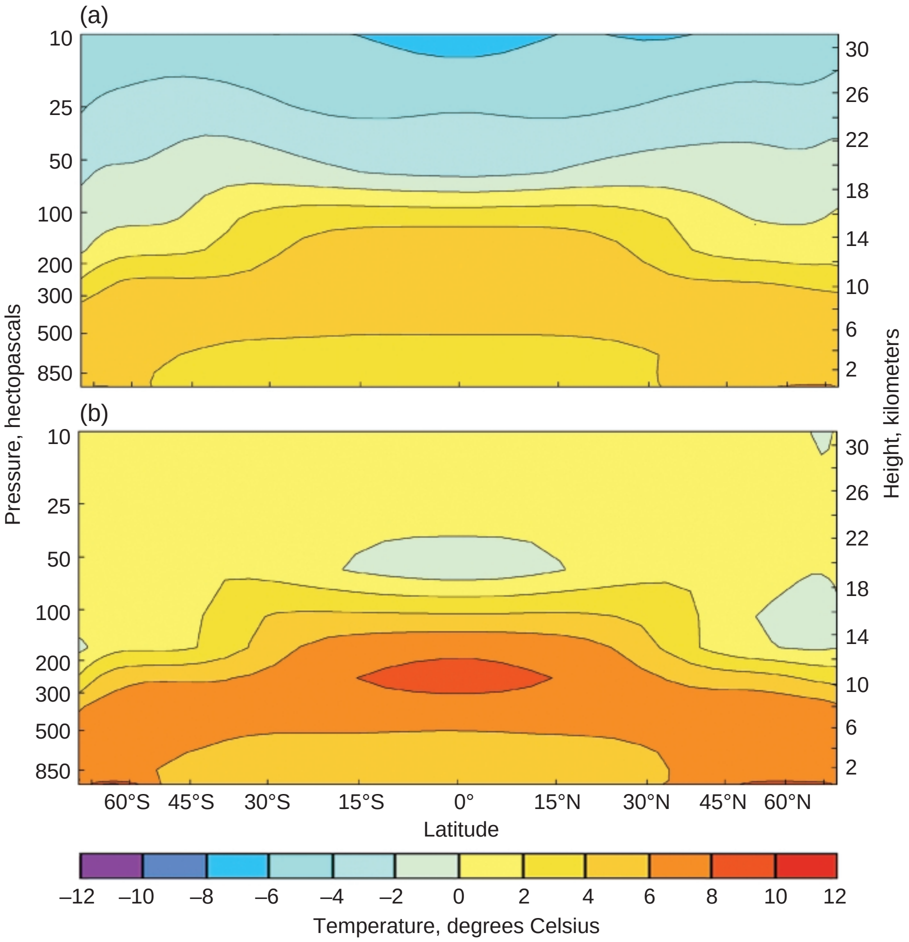
The team's observational data were land and ocean surface temperatures compiled at the Climatic Research Unit in Norwich, England, together with satellite-based tropospheric temperature measurements. Their model data came from a number of different sources: the Max Planck Institute for Meteorology in Hamburg, Germany, the Goddard Institute for Space Studies in New York, and the National Center for Atmospheric Research in Boulder, Colorado. Researchers from all of these organizations participated in the team. Other team members were with Livermore's Program for Climate Model Diagnosis and Intercomparison,



Geographic patterns of annually averaged temperature anomalies in (a) the lower troposphere and (b) at Earth's surface. Tropospheric temperature measurements are from polar-orbiting satellites, and surface measurements were made by thermometers. White areas denote missing data. Although the satellites have near-global coverage, the surface data have large gaps. Comparing satellite and surface data over areas of common coverage helps to explain some of the differential warming of the surface and troposphere. Anomalies are expressed relative to annual mean temperatures averaged over 1979 to 1998.

which routinely develops methods and tools for the diagnosis, validation, and intercomparison of global climate models.

The team first dealt with observed data. They found that removing El Niño and volcanic effects always led to larger warming trends in the residual surface and lower tropospheric data than in the raw observational data (where these effects were left in). Although El Niños caused a small net warming from 1979 to 1999, the El Chichón and Mount Pinatubo volcanic eruptions caused a larger net cooling during the same period. Removing both El Niños and volcanoes more clearly revealed the underlying warming trend in surface and tropospheric temperatures. It also helped to explain some of the differential warming of the surface and troposphere.



(a) Atmospheric temperature changes predicted to occur in response to a doubling of preindustrial levels of carbon dioxide. (b) Projected temperature response to a 2-percent increase in the Sun's energy output. Each factor that influences our climate has a characteristic "fingerprint." Scientists typically use computer models of the climate system to gain information on these fingerprints. In a model, it is possible to study the climatic effects of a single influence only, such as changes in atmospheric carbon dioxide. This is not feasible in the real world, where multiple factors that influence climate are changing simultaneously. Both (a) and (b), which are clearly dissimilar, show annual mean changes (in degrees Celsius) as a function of latitude and altitude.

"It's clear that if the Mount Pinatubo and El Chichón eruptions had not occurred, the lower troposphere would have experienced more pronounced warming," says Santer.

The team then removed volcanic and El Niño effects from model output and compared the results with observations. It is important to do this because even in a model with "perfect" representation of El Niño variability, the simulated El Niños would not necessarily occur at the same time that they happened in the real world. Also, some model experiments include the effects of well-observed volcanoes (such as Mount Pinatubo) but exclude other eruptions where less is known about the properties of the volcanic aerosols. Removing volcano and El Niño effects from both models and observations allows a fairer comparison of the underlying simulated and observed responses to human-caused changes in greenhouse gases.

The general conclusion from such comparisons was that removing volcano and El Niño effects from atmospheric temperature data improves the correspondence of the modeled and observed differential warming of the surface and troposphere over the last several decades. It does not, however, fully reconcile models and reality. The remaining differences are probably caused by problems with the observational temperature data; missing or inaccurately specified "forcings" in the climate model experiments, such as the neglect of land use changes or aerosol particles from biomass burning; and errors in the climate responses that the models predict.

Santer and his colleagues are actively investigating these possibilities. "We hope we've showed that this is a complex scientific issue," says Santer. "It can't be reduced to a one-minute sound bite. This issue is important, because it relates to our ability to evaluate climate models and to determine whether these models are useful tools for predicting climate change over the next century.”

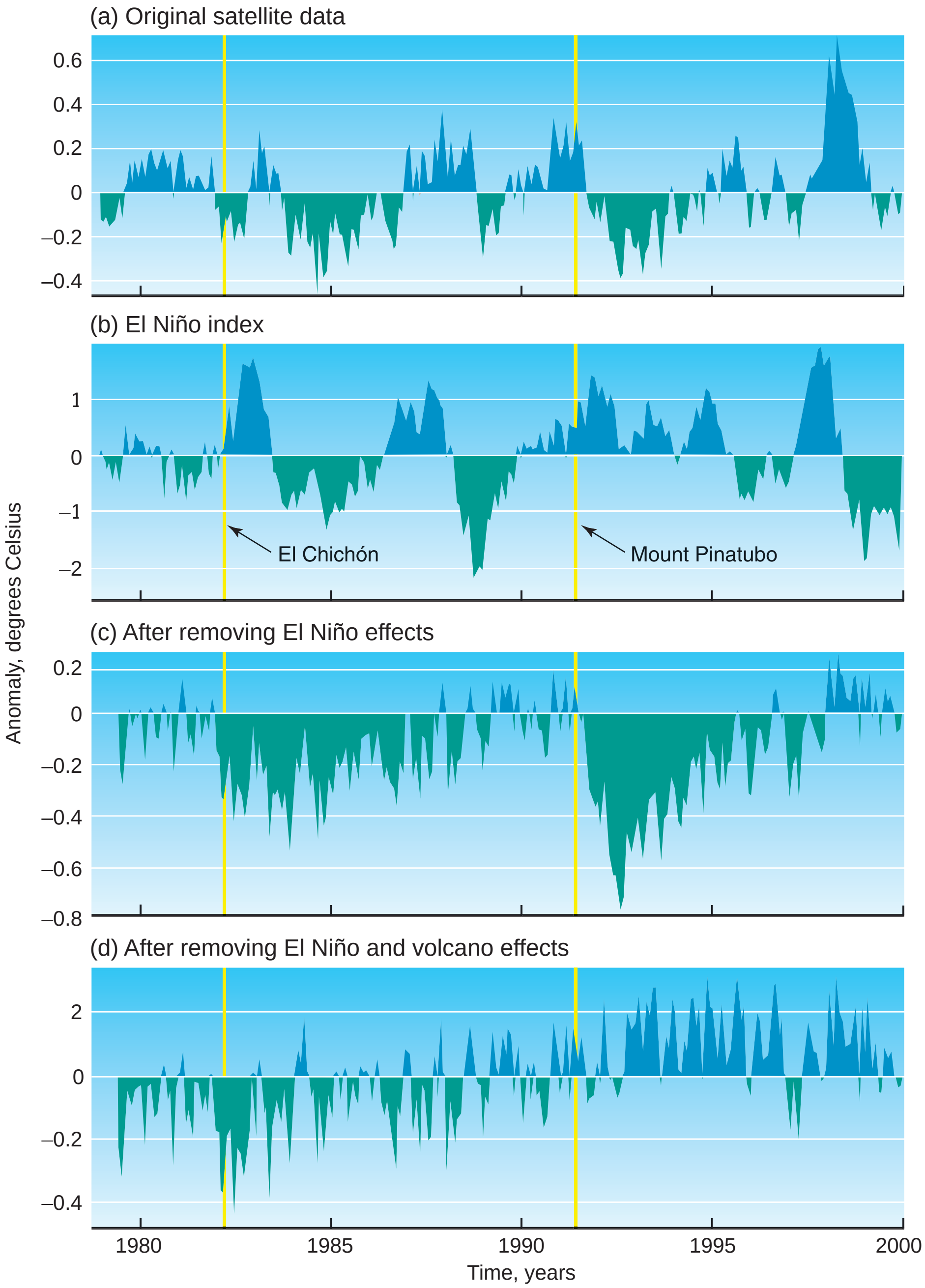
An Up-Close Look

The IPCC’s prediction that mean global temperatures will increase from 1.6° to 6°C by the end of this century isn’t especially useful for farmers and others whose livelihoods depend on the weather. They need more specific information on temperature increases expected in their area, whether it be Kansas or Kenya. They also need to know about changes in temperature extremes and in other important quantities such as precipitation. By providing improved simulations of climate change on regional scales, Livermore’s high-resolution climate simulations should allow for more accurate assessments of the effects of climate change on society.

Grids of 50 kilometers and less are already used in numerical weather prediction, which is much less computationally intensive than climate modeling because it requires much shorter forecasts (days rather than decades). For long-term climate modeling with resolution this fine, scientists had to await the arrival of huge computers with hundreds of processors operating simultaneously.

Duffy’s team is using the Community Climate Model 3, or CCM3, an atmospheric model developed by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. CCM3, the fourth-generation CCM model, is used at coarse resolutions in climate modeling centers around the world.

“For every change in horizontal resolution, there’s the problem of retuning the model,” says Duffy. Several physical processes such as convection, cloudiness, and precipitation are too small to be represented explicitly in climate models and are therefore treated using semiempirical parameterizations.



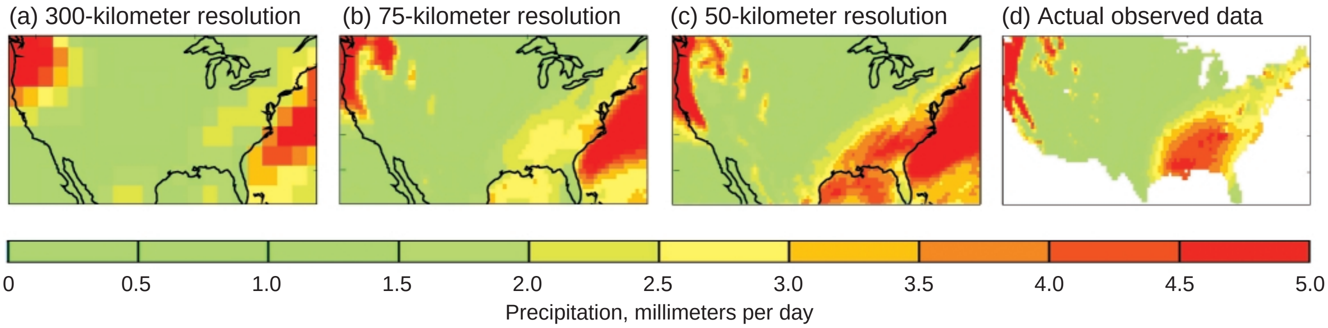
Some of the problems involved in removing the effects of El Niño variability and explosive volcanic eruptions from tropospheric temperature data. (a) In the original satellite-based temperature data, the cooling signal of the 1983 El Chichón eruption is masked by (b) one of the strongest El Niño events of the 20th century. After using an iterative method to successively refine estimates of El Niño and La Niña effects on tropospheric temperatures, these effects are removed from the original temperature data in (a). The cooling effects of the El Chichón and Mount Pinatubo eruptions are now more easily seen in (c). It is clear in (d) that removing both volcanoes and El Niño effects yields a pronounced warming trend that was not apparent in the original temperature data.

For example, although clouds may be too small to be represented directly in a grid cell, they must be accounted for because cloud cover affects the flow of radiation in the atmosphere. “So we parameterize their effects by modifying the optical properties of that layer of the atmosphere,” says Duffy.

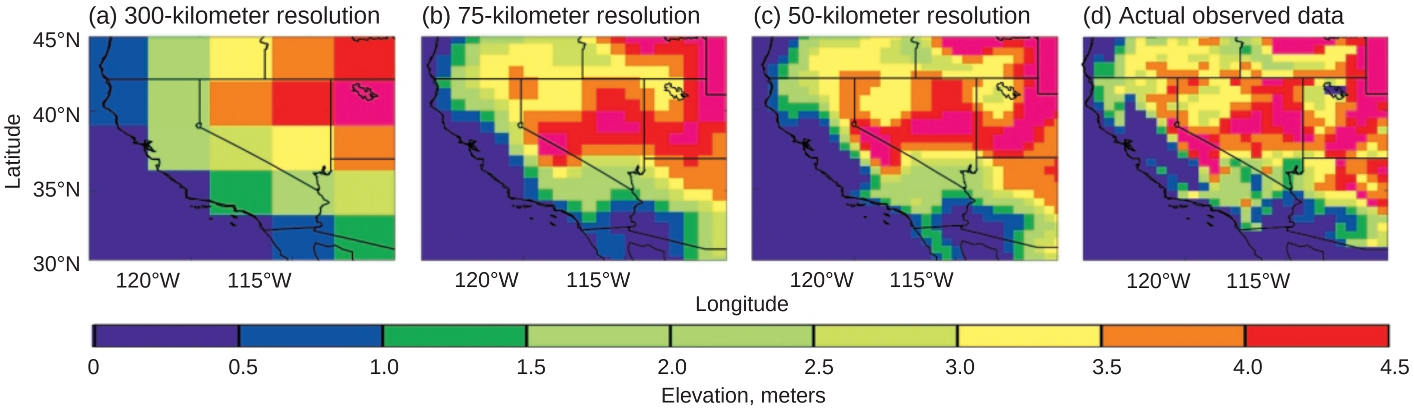
Because these parameterizations are not based on first-principles physics, they must be tuned carefully at each resolution. Tuning is done by adjusting parameter values to make the model’s results agree as closely as possible with observations. The 300-kilometer model has already been carefully tuned at NCAR to optimize results at that resolution. In collaboration with researchers at NCAR, Livermore researchers retuned their 75-kilometer model. Thus far, tuning done for the 75-kilometer model has also worked reasonably well with the 50-kilometer grid.

The team’s proof of principle with the 50- and 75-kilometer models was to compare their modeling results to observed data. Although, as Duffy notes, “the 50-kilometer model actually has better resolution than most of our observational data.” Perhaps not surprisingly, simulations using the 50-kilometer model agreed better with observed data than either a 75- or 300-kilometer grid. In some cases, there were substantial improvements.

When the team examined results in more localized regions of interest, the results were striking. The upper figure below shows simulated precipitation over the U.S. in December, January, and February using 50-, 75-, and 300-kilometer grids and compares all three to observed data. As the grid size shrinks, both small-scale and large-scale simulated precipitation features converge toward observations. This example shows


(a) 300-kilometer resolution (b) 75-kilometer resolution (c) 50-kilometer resolution (d) Actual observed data

The representation of December, January, and February precipitation over the U.S. improves as the resolution increases. Simulations using (a) 300-kilometer, (b) 75-kilometer, and (c) 50-kilometer resolution are compared with (d) actual observed data. Both fine- and large-scale aspects of the simulation improve as spatial resolution shrinks.


(a) 300-kilometer resolution (b) 75-kilometer resolution (c) 50-kilometer resolution (d) Actual observed data

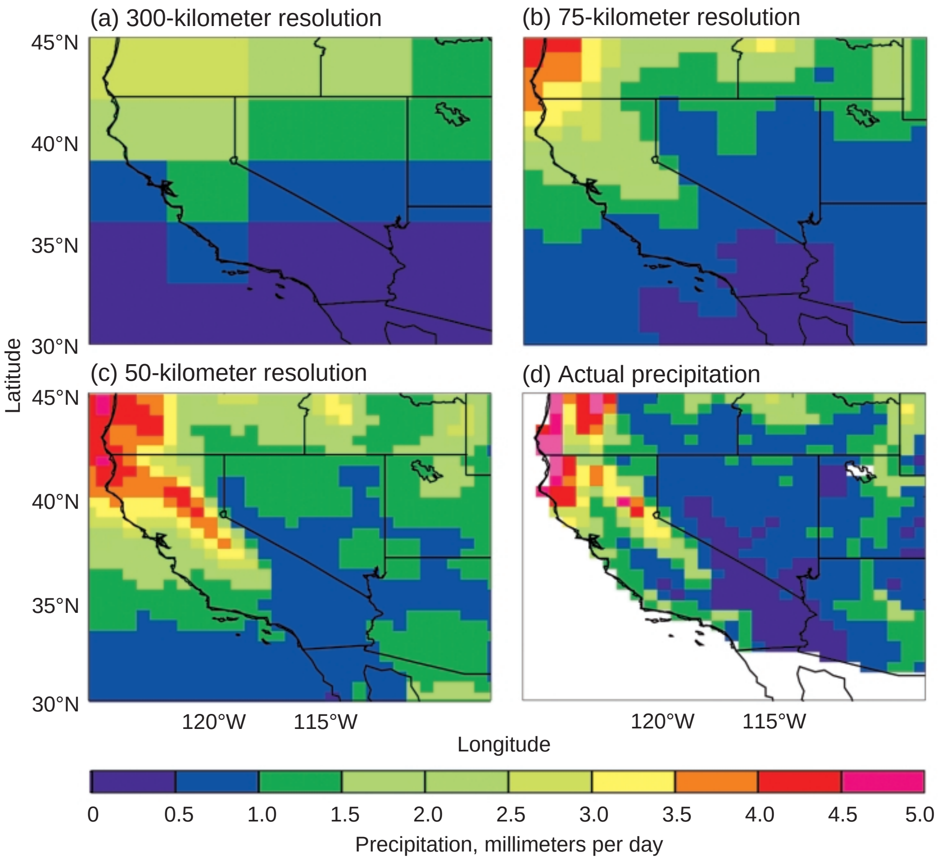
A comparison of elevations in California, as represented in models having (a) 300-kilometer, (b) 75-kilometer, and (c) 50-kilometer resolution, with (d) actual elevations at 50-kilometer resolution. Elevations in the models are lightly smoothed—evened out—to prevent sudden changes that cause numerical noise and contaminate the results. Even at 50-kilometer resolution, California’s Coast Range mountains and the Central Valley are not well represented.

that as spatial resolution becomes finer, not only is fine-scale detail added to the model results, but the large-scale aspects of the solution also become more realistic.

Simulations of California climate are a real test of climate models because of the great variability in climate that occurs within the state's relatively small area. Much of this variability results directly or indirectly from the state's major topographic features: the Coast Range, the Central Valley, and the Sierra Nevada. The figure at left, bottom, compares actual elevations at 50-kilometer resolution with topography as represented in models having 300-, 75-, and 50-kilometer resolutions. Although the topography is more realistic as the model resolution becomes finer, neither the coastal mountains nor the Central Valley are adequately represented in even the 50-kilometer model.

In part because of improved representations of topography, the model's ability to simulate precipitation in California improves dramatically as the resolution becomes finer. Nonetheless, 50-kilometer resolution is still not adequate to represent the state's Coast Range and Central Valley; even at this resolution, the simulation of precipitation differs noticeably from observations.

Simulations of Arctic climate similarly improve dramatically with finer resolution, but further improvements are nonetheless needed. Most coarse-resolution ocean–atmosphere–sea ice climate models produce poor simulations of the pattern of sea-level pressure in the Arctic region. Poor data for sea-level pressure result in unrealistic simulated atmospheric circulation, which in turn produces unrealistic distributions of sea ice thickness and concentrations and other problems. Accurate predictions of sea ice and of changes in sea ice because of global warming are essential. Sea ice strongly affects the climate not only in polar regions but also in far-flung regions through influences on the large-scale ocean circulation and on Earth's radiation balance.



A comparison of precipitation over California, as represented in models at (a) 300-kilometer, (b) 75-kilometer, and (c) 50-kilometer resolution, with (d) actual precipitation at 50-kilometer resolution.

In addition to these simulations of the present climate, Duffy's team has simulated the effects of increased greenhouse gases (that is, global warming) with the 75-kilometer-resolution model. This is the finest-resolution simulation of global warming performed to date and shows very different results from comparable simulations performed at coarser resolutions. Although the globally averaged responses of temperature and other variables to increased greenhouse gases are quite similar in the 75-kilometer model and in coarser-resolution models, the regional responses can be very different. For example, the figure on p. 12 shows predicted wintertime temperature changes between 2000 and 2100 in the U.S. The finer-resolution model shows regions of strong warming in the western U.S. and southeastern Canada, which are not predicted by the coarser-resolution model. In at least some cases, it seems clear that the results of the finer-resolution model are more believable.

Duffy's group has already fielded inquiries from experts interested in the effects of localized climate change on crop diseases, human health, water resources, and the like. Although the finer-resolution models are far from perfect, they may represent the best tools available today for assessing the regional effects of global warming.

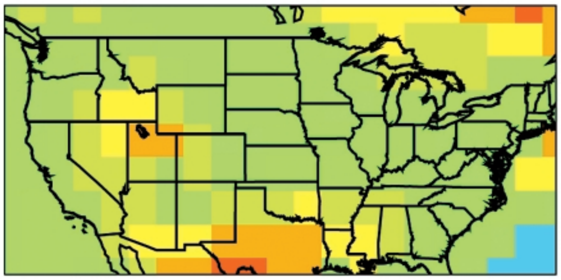
Getting It Right

A few months ago, a chunk of ice larger than Rhode Island collapsed on the east side of Antarctica. It was the largest single event in a series of ice shelf retreats there extending back 30 years. Temperatures at the Antarctic Peninsula have increased by 2.5°C over the last 50 years, much faster than the global average. Getting Arctic and Antarctic models right is crucial for determining what may happen to sea levels around the world as temperatures continue to rise.

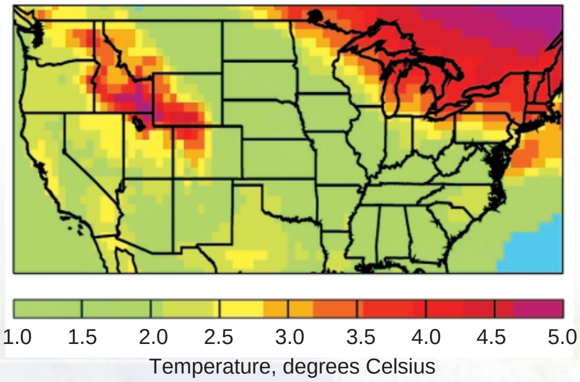
Closing in on how much humans are responsible for the changes in our planet's climate is equally important. Getting it right matters to us all.

—Katie Walter

(a) 300-kilometer resolution



(b) 75-kilometer resolution



Predicted temperature increases from 2000 to 2100 for December, January, and February at resolutions of (a) 300 kilometers and (b) 75 kilometers. The predicted data from the model with finer resolution are much more specific and useful.

Key Words: climate modeling, Community Climate Model 3 (CCM3), global warming, National Center for Atmospheric Research (NCAR).

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For information about the Intergovernmental Panel on Climate Change:

www.ipcc.ch/

For information about Livermore's Program for Climate Model Diagnosis and Intercomparison:

www-pcmdi.llnl.gov/