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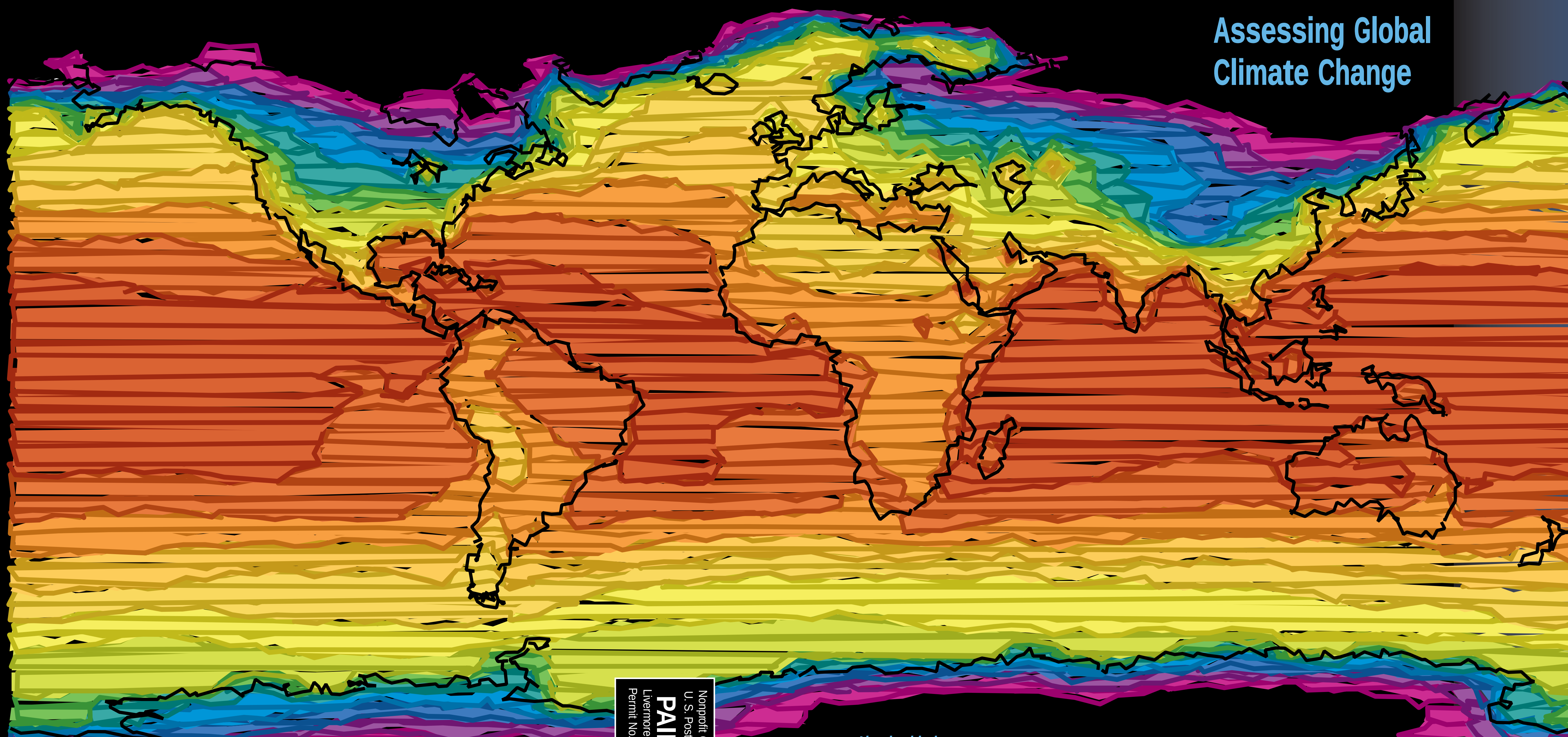
Science & Technology REVIEW

Assessing Global Climate Change



Also in this issue:

Six New R&D 100 Awards

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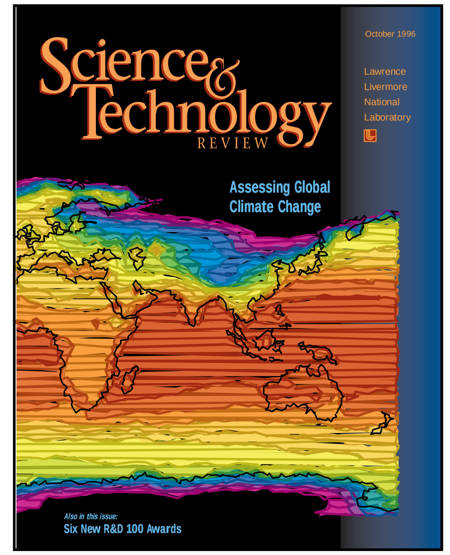
About the Cover

The stylized map is taken from our feature article on global climate modeling, beginning on p. 6. The actual Figure 5a (p. 12) in the article shows the ten-year mean surface temperature variability in December, January, and February from 1979 to 1988. Using massively parallel processing computers at Livermore, the Laboratory performs calculations of this type in research coordinated with the international Atmospheric Model Intercomparison Project.



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About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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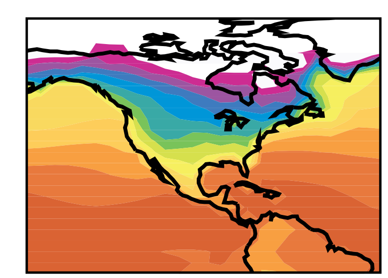

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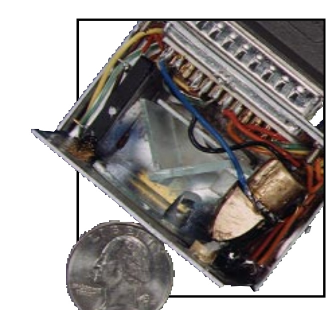

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Technique to hunt dark matter could search for planets

An astrophysics technique used to search for "dark matter" may prove valuable in finding planets orbiting suns near the center of our galaxy. That is the view of Laboratory scientists David Bennett and Sun Hong Rhie in a paper for the *Astrophysical Journal*.

Bennett is part of an international team that is searching for dark matter: nonvisible astrophysical objects—such as black holes, white dwarfs, brown dwarfs, and neutron stars—that are estimated to account for 90% of gravitational mass in our galaxy. Rhie is an expert on theoretical aspects of gravitational lensing by double stars and planetary systems.

In hunting for dark matter, astrophysicists use a method known as microlensing, in which gravity from a large dark object passing in front of a distant star makes the light from that star appear brighter for a time. This change in brightness can be graphed in the form of a light curve, typically a bell shape.

If the same search technique is oriented toward the center "bulge" of our galaxy, Bennett and Rhie say, faint stars could be used to microlens more distant and brighter stars. A planet associated with the faint star could then be detected within the resulting light curve. The planet would appear as a brief modulation of the bell-shaped curve.

The work by Livermore astrophysicists shows that an ambitious microlensing program could detect planets ranging from Jupiter down to the mass of less than ten Earths. While there are several other techniques for finding planets, microlensing appears to be the only ground-based technique that is sensitive to small planets.

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Livermore provides spectrometer to Poland

Polish border guards are in a better position to do on-the-spot analysis of suspicious materials entering or leaving their country, thanks to a portable gamma-ray spectrometer the Laboratory has provided by way of the Department of Energy and Department of State.

Before delivery of the device in June, the only way Polish border guards could analyze suspicious materials was by sending them off to the Polish Central Lab. At an international forensics conference last fall, the director of the Polish Central Lab voiced the need for a portable system, noting more than 100 border incidents involving suspicious materials in 1995.

The surplus spectrometer was provided by the Laboratory's Emergency Preparedness and Response Division, a unit of the Nonproliferation, Arms Control, and International Security directorate. In addition to tracking and analyzing materials at Polish border crossings, the spectrometer will be used for radiological monitoring.

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Portable treatment system promises cleanup savings

Automated, portable groundwater treatment facilities developed by Laboratory scientists promise to save time and millions of dollars in environmental cleanup costs.

Spurring development of the portable treatment units is cleanup of groundwater beneath the Livermore site. Groundwater contamination is primarily volatile organic compounds largely left over from the time when the site was a naval air training station. There are five stationary treatment facilities currently in operation at the Livermore site, treating water pumped from 27 extraction wells.

Through geologic and geophysical analysis of subsurface conditions and the use of computer models, scientists can estimate the optimum locations for extraction wells that connect to surface treatment facilities. Because those locations change over the course of cleanup operations, the versatility of the new portable units will allow Livermore scientists to attack specific areas of contamination as the cleanup proceeds—at lower costs for the facility, piping, and manpower (for more information see *S&TR* Jan./Feb. 1996 and May 1996).

Laboratory remediation experts expect to save more than $10 million with the new portable facilities, which will substitute for previously planned stationary treatment facilities. The portable treatment approach is also expected to speed cleanup by allowing remediation experts to move the treatment systems easily to different locations to most efficiently remove the pollution.

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Lab achieves chip production breakthroughs

Two breakthroughs by Laboratory researchers could help U.S. manufacturers produce computer chips with 1,000 times more memory than today's chips—and do so ten times faster than current technology.

The advances appear to largely overcome two critical hurdles that could have blocked the use of extreme ultraviolet (EUV) light to make computer chips in a process called EUV lithography. EUV lithography would allow 21st century computer chip makers to work with light wavelengths 20 times shorter than those of today's technology, reducing line widths or feature sizes on chips from 0.35 to 0.1 micrometer and smaller.

Lawrence Livermore's advances came in two key areas:

- A critical 20- to 50-fold improvement in accuracy for measuring the surface shapes of optical components used in the lithography process.
- A 300,000-fold reduction in the number of defects in the multilayer-coated reflective masks used to transfer circuit patterns onto silicon wafers, or chips.

The reduction in mask defects springs from an ion beam sputter deposition system developed by the Laboratory and Veeco Instruments Inc, a Plainview, New York, semiconductor equipment company.

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Lab conducts test of airborne multisensor pod

Researchers from the Laboratory's Nonproliferation, Arms Control, and International Security directorate conducted airborne tests earlier this year of a multisensor unit they developed to remotely detect small quantities of chemicals and radionuclides. Designed primarily for weapons treaty verification, the unit has potential applications in environmental monitoring or in the event of an industrial accident or natural disaster.

The 5-m-long by 1-m-wide cylindrical unit, designed to attach to the underside of an aircraft wing, is called the Effluent Species Identification (ESI) pod. A miniature laboratory, the pod contains four effluent sensors: an ion mass spectrometer for identifying chemicals, a radionuclide analyzer to detect radioactivity, a krypton sampler, and an aerial atmosphere sampler. Sensor guidance is provided by a target tracking system located in a small revolving turret on the underside of the pod.

Laboratory researchers developed one of the sensors and integrated it and the three others into the ESI pod, which they also developed. Collaborating with the Laboratory were Pacific Northwest National Laboratory and the Savannah River Technology Center. The pod is one of several being developed as part of the Department of Energy's Airborne Multisensor Pod System, a nonproliferation program involving several DOE laboratories, the U.S. Navy, and private industry.

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Seeping gases can aid detection of nuclear tests

Tiny amounts of radioactive rare gases that seep to the surface from underground nuclear explosions could foil nations secretly trying to evade a proposed ban on nuclear tests. This finding by Lawrence Livermore scientists offers international agencies another possible tool for monitoring a nuclear weapons test ban.

In the August 8 issue of the British journal *Nature,* the scientists reported that gases produced by nuclear explosions and released along natural faults and cracks in the Earth can be used to detect clandestine nuclear tests.

The finding is based on an experiment conducted in 1993 at the Department of Energy's Nevada Test Site. In the experiment, the Lawrence Livermore team mixed small amounts of two nonradioactive gases, helium-3 and sulfur hexafluoride, into chemical explosives in a non-nuclear test that simulated a deeply buried underground nuclear explosion.

Says geophysicist Charles Carrigan, who led the Livermore team: "Our experiment shows that people who attempt to conduct a clandestine nuclear test will not have any guarantee they can hide it from detection during an on-site inspection."

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Patents

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Thomas E. McEwan George D. Craig	**Ultra-Wideband Receiver** U.S. Patent 5,523,760 June 4, 1996	A single-ended ultra-wideband receiver with a self-regulating amplifier that maintains a predetermined average output voltage. An input channel is connected to one input of the amplifier and a strobe generator is connected to the input channel. A single Schottky detector diode or a pair of series-connected Schottky detector diodes are placed in the input channel.
Bernhard Rupp	**Electrorheological Crystallization of Proteins and Other Molecules** U.S. Patent 5,525,198 June 11, 1996	The process of producing an electrorheological crystalline mass of a molecule by dispersing the molecule in a fluid and subjecting the molecule dispersion to a uniform electrical field for a period of time during which the electrorheological crystalline mass is formed. Crystallization is performed by maintaining the electric field after the electrorheological crystalline mass has formed, during which at least some of the molecules in the mass form a crystal lattice.
Rajeev R. Rohatgi Thomas E. Cowan	**Fan-Fold Shielded Electrical Leads** U.S. Patent 5,525,760 June 11, 1996	Electrical leads that are shielded, vacuum- and cryogenic-temperature-compatible, totally nonmagnetic, and bakable. They are suitable for multiple signal and/or multiple layer applications, and the leads are suitable for voltages in excess of 1,000 volts. The assembly is easily fabricated by simply etching away certain areas of a double-clad substrate to form electrical leads on one side.
Brian D. Andresen Joel D. Eckels James F. Kimmons David W. Myers	**The Portable Gas Chromatograph–Mass Spectrometer** U.S. Patent 5,525,799 June 11, 1996	An organic chemical-analysis instrument that has sensitivity and mass resolution characteristics of laboratory benchtop units, but is portable and has low electrical energy consumption. The instrument weighs less than 32 kilograms and uses less than 600 watts at peak power. The instrument incorporates a modified commercial quadrupole mass spectrometer to achieve the instrument sensitivity and mass resolution, comparable to larger laboratory instruments.
T. Hayden Stephen A. Payne Joseph S. Hayden John H. Campbell Mary Kay Aston Melanie L. Elder	**Phosphate Glass Useful in High Energy Lasers** U.S. Patent 5,526,369 June 11, 1996	A laser system using phosphate laser glass components having an emission bandwidth of >26.29 nm and a coefficient of thermal expansion, from 20 to 300°C of <145 ¥ 10^{-7}/K. The laser glass components consist of a multioxide composition, Al_2O_3 for chemical durability and thermal mechanical properties, and K_2O. The system operates at an energy level of <0.1 MJ. The glass is desirable for laser operation and manufacturing.
Georg Albrecht E. Victor George William F. Krupke Walter Sooy Steven B. Sutton	**High Energy Bursts from a Solid State Laser Operated in the Heat Capacity Limited Regime** U.S. Patent 5,526,372 June 11, 1996	A heat-capacity laser operating in two modes: a firing cycle and a cooling cycle. In the firing cycle the solid-state laser is not cooled. In heat capacity operation, as lasing proceeds, the active medium will heat up until it reaches a maximum acceptable temperature. The waste heat is stored in the active medium itself. After lasing is complete, the active media are cooled to the starting temperature, and the laser is ready to fire again.
James L. Kaschmitter Steven T. Mayer Richard W. Pekala	**Carbon Foams for Energy Storage Devices** U.S. Patent 5,529,971 June 25, 1996	A double-layer capacitor of carbon foam electrodes. Several foams may be produced—including aerogels, xerogels, and aerogel-xerogel hybrids—that are high-density, electrically conductive, dimensionally stable, and machinable. The electrodes are formed from machinable, structurally stable carbon foams derived from the pyrolysis of organic foams. Integration to form the capacitor is achieved using lightweight components.

The Importance of Climate Change

ONE grand challenge facing the international scientific community is determining the record of the Earth's climate since the last ice age and assessing whether humans have significantly impacted the climate in recent years. If we conclude with confidence that human activities do indeed affect climate and that the consequences pose real dangers, responding to such dangers will present tremendous political and economic challenges to every nation. Working on such a problem is a worthy mission for a national laboratory; Livermore's multidisciplinary expertise enables us to contribute substantive solutions.

Our understanding of climate variability has increased greatly over the past few decades because the record of climate since the last glaciation has been developed through studying sediments from melting episodes in ice sheets and ice caps, and pollen, dust, and isotopic records in ice caps and lake and river sediments. We have come to appreciate that we live in a system that has experienced great temperature and precipitation swings in the recent millennia.

A consequence of this insight is that interpreting global warming in simple terms such as an average warming of a fraction of a degree Celsius over the Earth's surface could greatly underestimate the actual effects. Change will have a regional pattern, causing warming in some regions and cooling in others, as global patterns of precipitation and other atmospheric variables shift. In particular, any perturbation of the ocean currents that make up the thermohaline cycle (believed to be stable for the past several thousand years) could produce dramatic regional thermal effects such as cooling Europe by several degrees Celsius and drying the center of the North American continent.

We know from both the historical and archaeological records about events such as the Little Ice Age in Europe and hundred-year droughts in North and South America. If our actions produce similar climate change, the human consequences—ecological, political, and economic—could rival any natural disaster in human record. But before worrying too much about disasters, we must have more information.

The attribution of climate change to human activities, coupled with increasing confidence (now not available) in the ability to predict the effects of climate change, will lead to the need to evaluate the options, costs, and credibility of measures to mitigate the effects of such change. This evaluation will require an unprecedented combination of scientific, economic, and policy skills to reassure the political system if the consensus required to modify the economies of the developed world and the path of the developing world is to be achieved. Unprecedented confidence in the reliability of scientific assessments will be necessary.

The work described in this issue beginning on p. 6 summarizes several LLNL research projects that have advanced our understanding of the climatic consequences of human activities and increased our confidence to detect climate change and determine if it is linked to humans. We have shown that the burning of fossil fuel that increases atmospheric carbon dioxide and causes warming globally also injects sulfate aerosols that promote local cooling. This knowledge makes it possible to predict patterns of global warming and cooling from signatures that are associated with human activities.

In developing tools for testing climate models, we have statistically compared the past climate record with predictions based on fossil fuel consumption records. We found remarkably suggestive agreement in the geographic patterns of warming and cooling. While these results are currently the subject of controversy regarding the evaluation processes of the Intergovernmental Panel on Climate Change, there is strong consensus within the scientific community that the data suggest a human origin for the global warming that is currently being observed.

Livermore's strengths and role in climate studies come from several capabilities. We are conducting an international program to create standard data records and methodologies to test the credibility of climate models. Our scientists study inadequately characterized mechanisms of climate such as atmospheric chemistry, aerosol, and radiation effects, and they develop models that allow realistic coupling of atmospheric and ocean processes. Modeling activities grow with collaborations such as the Accelerated Strategic Computing Initiative (ASCI), which links us to new computational capabilities within the Department of Energy. Measurements of the carbon-14 record of the modern carbon cycle and the isotopic records of the paleoclimate are provided by projects conducted at our Center for Accelerator Mass Spectrometry.

Together, our powerful computational, modeling, and measurement capabilities give us the confidence that Lawrence Livermore will continue to play a major role in responding to this critical scientific challenge.

■ Jay C. Davis is the Associate Director for Environmental Programs.

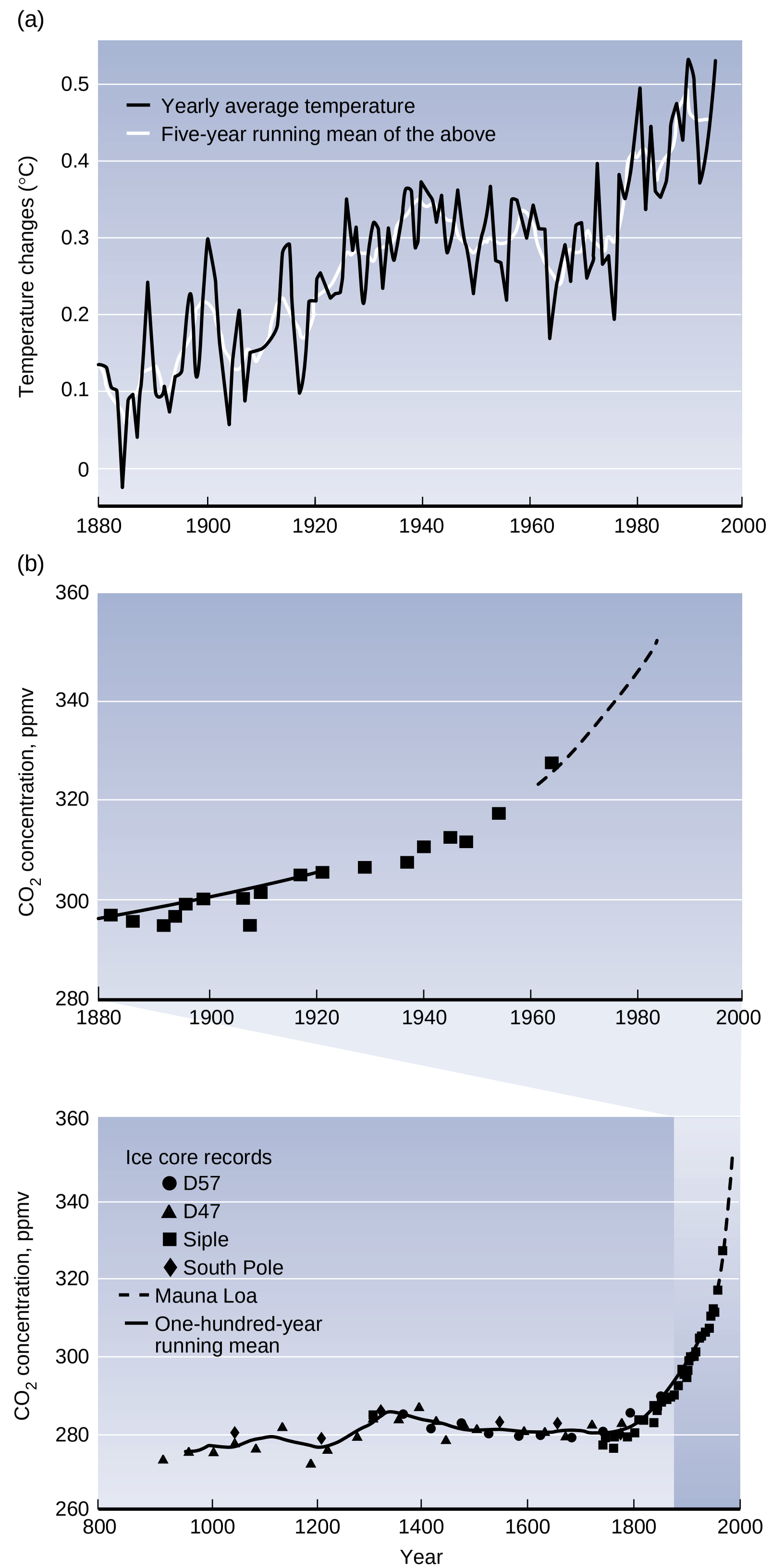

Figure 1. (a) On average, the Earth's surface has warmed slightly over the last century.[2] (b) CO_2 concentrations over the past 100 and 1,000 years from Antarctica ice-core records and (since 1958) Mauna Loa, Hawaii, measurement site.[3]

effects of greenhouse gases. Suspended in the atmosphere, these micrometer-size particles tend to cool the Earth by scattering sunlight back into space. The aerosols result from photochemical reactions of sulfur dioxide emitted into the atmosphere through the combustion of fossil fuels.

To test that hypothesis, we developed the world's first global chemistry–climate model. This model involved combining three others: (1) the LLNL version of an atmospheric model developed by the National Center for Atmospheric Research for use by the global climate research community, (2) a simple ocean model that represents conditions of the ocean's upper layers (within 50 meters from the surface), and (3) the GRANTOUR tropospheric chemistry model developed at Livermore. GRANTOUR simulates the transport, transformation, and removal of various sulfur species in the troposphere (lowest 10 to 20 kilometers of the atmosphere). It was needed for predicting the formation of sulfate aerosols from sulfur dioxide gas released into the atmosphere.

We used the chemistry–climate model in a series of experiments that were the first attempt to simulate how temperatures are affected by combinations of carbon dioxide and sulfate aerosols.[4] Numerical integrations began with a control run using the pre-industrial CO_2 level and no sulfur emissions. Next, we ran an experiment to simulate CO_2 increased to the present-day carbon dioxide level and examined the difference in temperature compared to the control run (Figure 2a). The next run combined CO_2 and sulfate aerosols, and again we considered the difference compared to the control run (Figure 2b). These two sets of results can be compared to the observed temperature changes. Figure 2c depicts the difference between temperature data taken in 1948 and 1988. The run depicted in Figure 2b, which included both CO_2 and sulfur emissions, predicted results much closer to the temperature difference map, which is based on observations.

These results showed that the sulfate aerosols offset CO_2-induced warming and could even produce net cooling in regions of the Northern Hemisphere where sulfur emissions are highest.[4] Follow-up statistical studies found that the patterns of climate change resulting from both greenhouse gases and sulfate aerosols are a closer match to actual observed temperatures than patterns of change predicted by models that only include greenhouse gases.[5,6]

These Laboratory results are included in a United Nations report prepared by the Intergovernmental Panel on Climate Change.[3] That report, written by dozens of internationally prominent scientists including several from Lawrence Livermore, contains the most recent model-generated predictions of temperature change to the year 2100 (an increase between 1 and 3.5°C) and includes the presence of both sulfate aerosols and greenhouse gases. The sulfate aerosols counteract global warming to some extent; however, the potential warming that the report describes may still be significant enough to pose a threat to human economies and natural ecosystems. Also, it is important to note that greenhouse gases remain in the atmosphere far longer than sulfate aerosols, and thus their effects would dominate even more if present sulfur and greenhouse emission rates continue.

Modeling the Carbon Cycle

Most of the carbon dioxide added to the atmosphere by human activities results from burning fossil fuels,

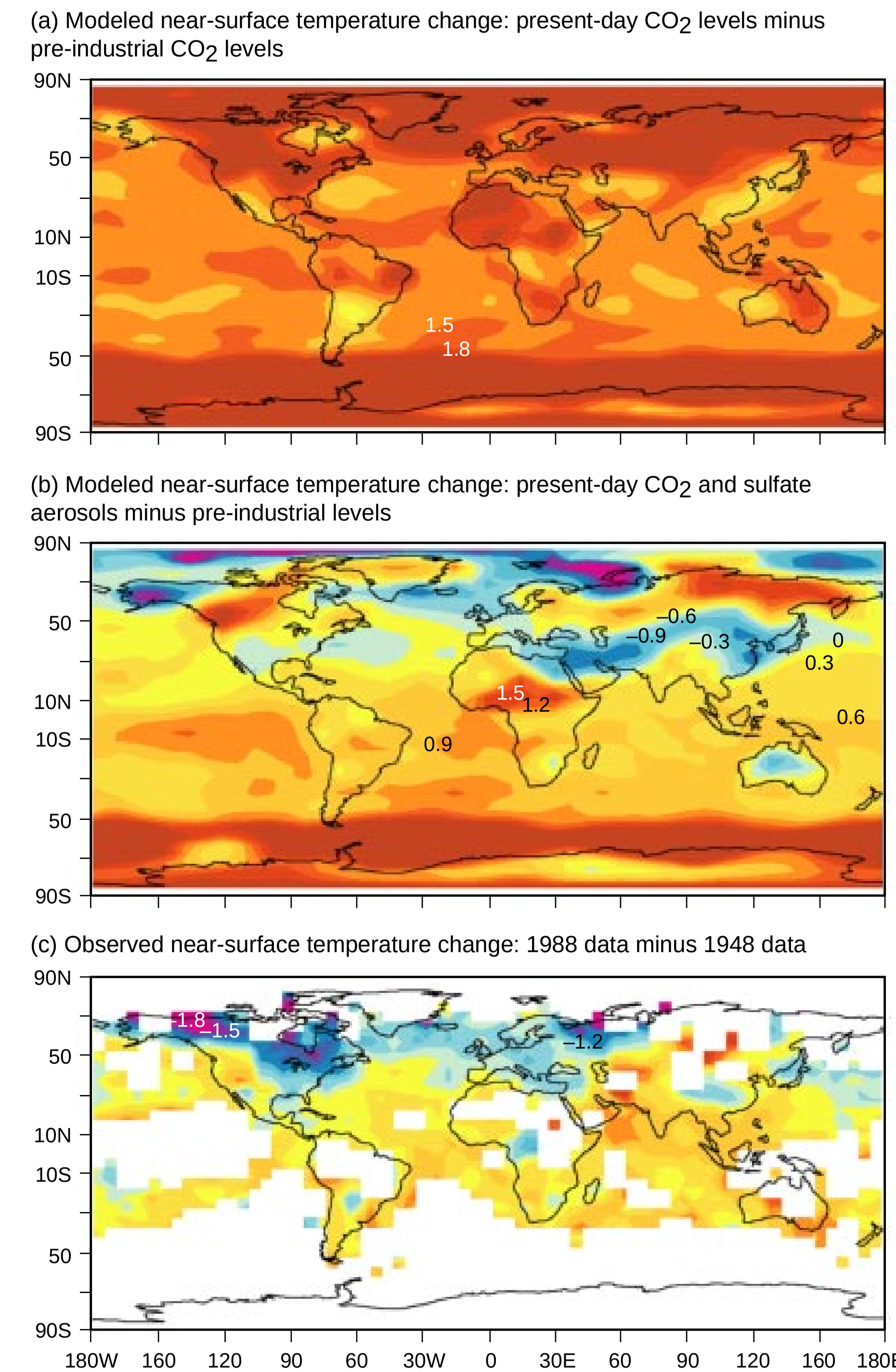

Figure 2. Temperature-change maps show that observed patterns of near-surface temperatures are in better accord with predictions from models that consider CO_2 and sulfur emissions than with models that consider CO_2 only. Notes: all temperature changes are for Sept., Oct., and Nov. in °C; white areas in (c) indicate missing data.

PCMDI: Reducing Systematic Model Errors

Diagnosing why climate models behave the way they do is a nontrivial task: as models have become more complex, the disagreement among them—as well as that between models and observations[7]—remains significant, yet poorly understood. The Laboratory established the Program for Climate Model Diagnosis and Intercomparison (PCMDI) in 1989 to develop improved methods and tools for evaluating global climate models.

As part of its mission, the PCMDI is coordinating the Atmospheric Model Intercomparison Project (AMIP) on behalf of the international World Climate Research Programme. In this project, virtually all of the world's 30 atmospheric modeling groups are simulating the climate of recent decades, using observed sea surface temperature as a boundary condition.

AMIP has already gained substantial insight into atmospheric models.[8] For the first time, disagreement among models can be assessed precisely. For example, PCMDI researchers have found that the models generally agree well in their predictions of temperature and winds but disagree widely in their predictions of clouds. Systematic errors common to all models have also been revealed, e.g., discrepancy between predicted and observed absorption of solar energy in clouds.

In addition to its work for the AMIP, the PCMDI has entered into a project with the World Climate Research Programme to compare the performance of various coupled ocean–atmosphere–sea-ice models. These more complete models are being used in forecasts of 21st century global temperatures.

The PCMDI also has provided tools and information to facilitate climate model analysis. These include model documentation, a database of observations for comparison with model output, and a visualization and computation system for both model-produced and observed climate data.[9]

although substantial amounts of CO_2 (20%) result from less plant absorption due to deforestation. Only about half the CO_2 that is released into the atmosphere remains there, however, and what happens to CO_2 that does not remain in the atmosphere is uncertain. As carbon dioxide comes in contact with the sea surface, some is absorbed into the ocean; as it comes in contact with the leaves of plants, some is absorbed and transformed into plant tissue. However, the amounts and rates at which the sea or plants can absorb CO_2 are still poorly characterized. Hence, our models cannot adequately predict how much of the approximately 6 billion tons per year of CO_2 that is released today from human activities will be found in the ocean, in plants, or in the atmosphere 10, 20, or 100 years from now.

We must narrow these uncertainties in order to make reliable predictions of the climatic consequences of fossil fuel burning and deforestation. To do this, we are developing a carbon-cycle model that includes transport of CO_2 in the atmosphere, the consumption and respiration of CO_2 by terrestrial ecosystems, and the absorption and emission of CO_2 by the oceans. The model incorporates a treatment of carbon isotopes that is more detailed than can be found in any other global carbon-cycle model. Carbon isotope data from biomass and ice samples tested at facilities such as LLNL's Center for Accelerator Mass Spectrometry are contributing to our confidence in the model's predictive capability. Computer experiments using an initial version of this model show that simulations of changes in carbon storage over the past two centuries are consistent with our understanding of the history of deforestation and with observed changes (see Figure 3).

The oceanic portion of our carbon-cycle model incorporates models of ocean circulation, chemistry, isotopic processes, and biology. We use a state-of-the-art ocean GCM with a dynamic and thermodynamic sea-ice model that runs on massively parallel computers. This GCM model shows how dissolved carbon dioxide and other chemicals impact the carbon cycle; it includes global distributions of natural and nuclear-explosive-produced radiocarbon. With this model, we have simulated oceanic absorption of carbon for the past few centuries. To our knowledge, this is the first completed ocean biogeochemistry model in use today.

The terrestrial ecosystem portion of our carbon cycle model, still under development, is based on a detailed model of how a terrestrial ecosystem functions and on a detailed simulation of biochemical processes that occur during photosynthesis. Already widely published, the model successfully simulates carbon fluxes at specific sites where detailed measurements have been made. As a consequence, the terrestrial portion is considered by many to be the model of choice for application to forest growth rates. The fact that this model is physically based and well tested gives us confidence that we will be able to incorporate it into the larger carbon-cycle model.

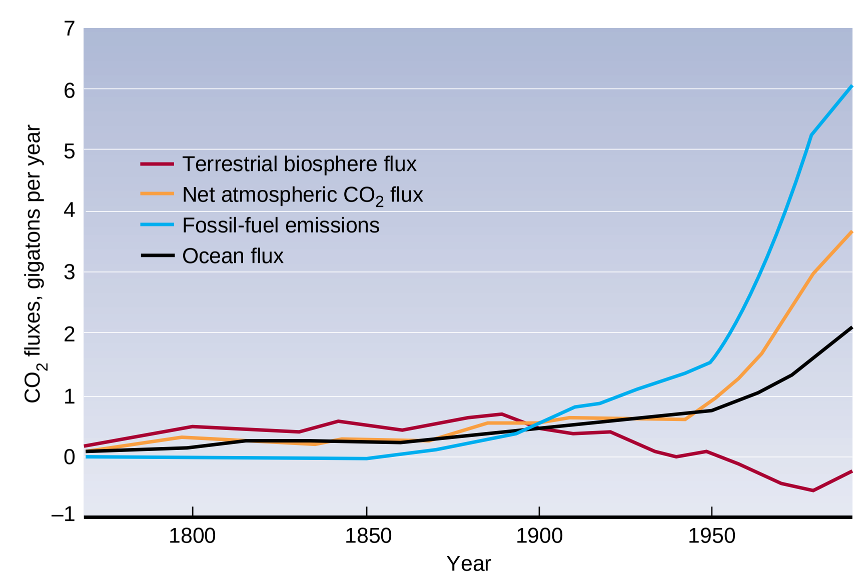

Figure 3. Carbon dioxide fluxes into and out of the atmosphere. The red curve shows that the terrestrial biosphere (plants and soils) was a net absorber of carbon from the atmosphere until about 1950. The observed yearly change in the carbon content of the atmosphere (gray line) is equal to the measured fossil-fuel emissions (pink line) plus the modeled flux of carbon into or out of the ocean (black line) plus the residual flux into or out of the terrestrial biosphere (red line). Accuracy of this residual CO_2 value is dependent on the accuracy of the measured or modeled data comprising the other terms.

Applying Advanced Computing Techniques

Typical atmospheric GCMs calculate temperature, pressure, wind velocity, and dozens of other variables at millions of points around the globe. Each calculation must be repeated to advance the simulated climate hour by hour. However, the cost of computational time severely limits the use of GCMs, even on the fastest of today's supercomputers.

To address this problem, the DOE established the Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) Program. With support from CHAMMP, we modified an atmospheric GCM to run on the new-generation computers that promise significantly greater speed. Our modified GCM is specifically designed to run on massively parallel processing computers that simultaneously employ large numbers of arithmetic processors with memory distributed locally to each.

We have used a technique known as domain decomposition to distribute the calculation across many processors. As shown in Figure 4, the basic idea is to divide the grid points covering the planet into rectangular "tiles," or subdomains. Each of these subdomains is assigned

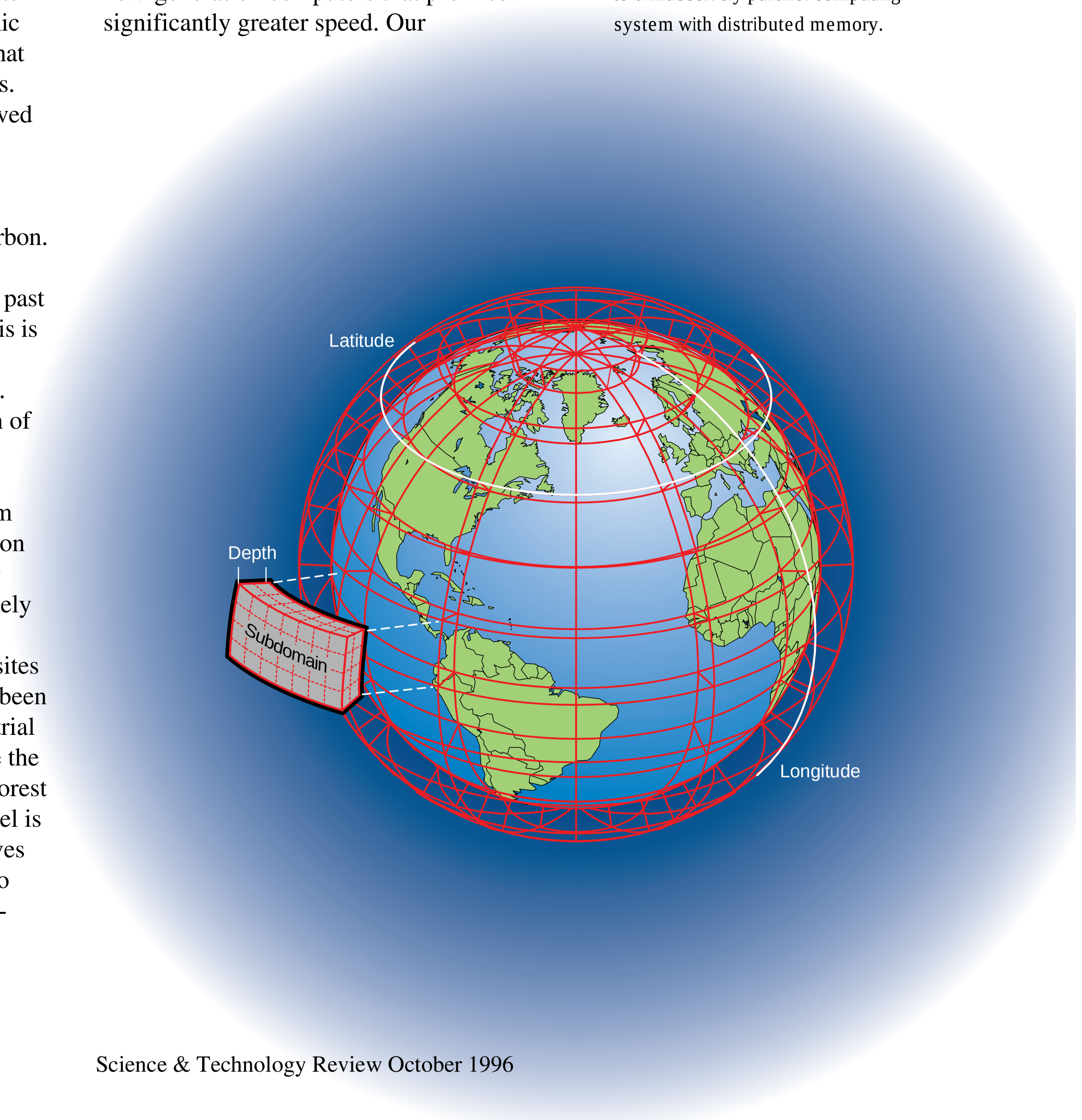

Figure 4. LLNL scientists use this two-dimensional domain decomposition of the globe to accomplish an efficient distribution of climate-model calculations to a masssively parallel computing system with distributed memory.

to a processor. A particular processor is responsible for advancing the solution only for those grid points contained within its subdomains. To do this, however, requires information about the state of the grid points just outside the subdomain. Interprocessor communication of this data surrounding the subdomain is accomplished on the computer's internal network via explicitly programmed message-passing techniques. Our challenge is to minimize this communication yet ensure that all available processors are assigned roughly equal amounts of work.

We perform both atmospheric and oceanic GCM calculations very rapidly as a result of the availability of the Cray T3D and other massively parallel machines at Livermore. In the largest series of calculations to date, we performed an ensemble of 20 simulations for the Atmospheric Model Intercomparison Project (see box, p. 10). Different calculations varied only in their initial conditions, allowing an assessment of the natural variability of climate due to the inherently chaotic nature of the atmosphere. Understanding such natural variability will allow better climate system predictions (Figure 5). We are analyzing this ensemble data and preparing it for dissemination to the wider climate modeling community.

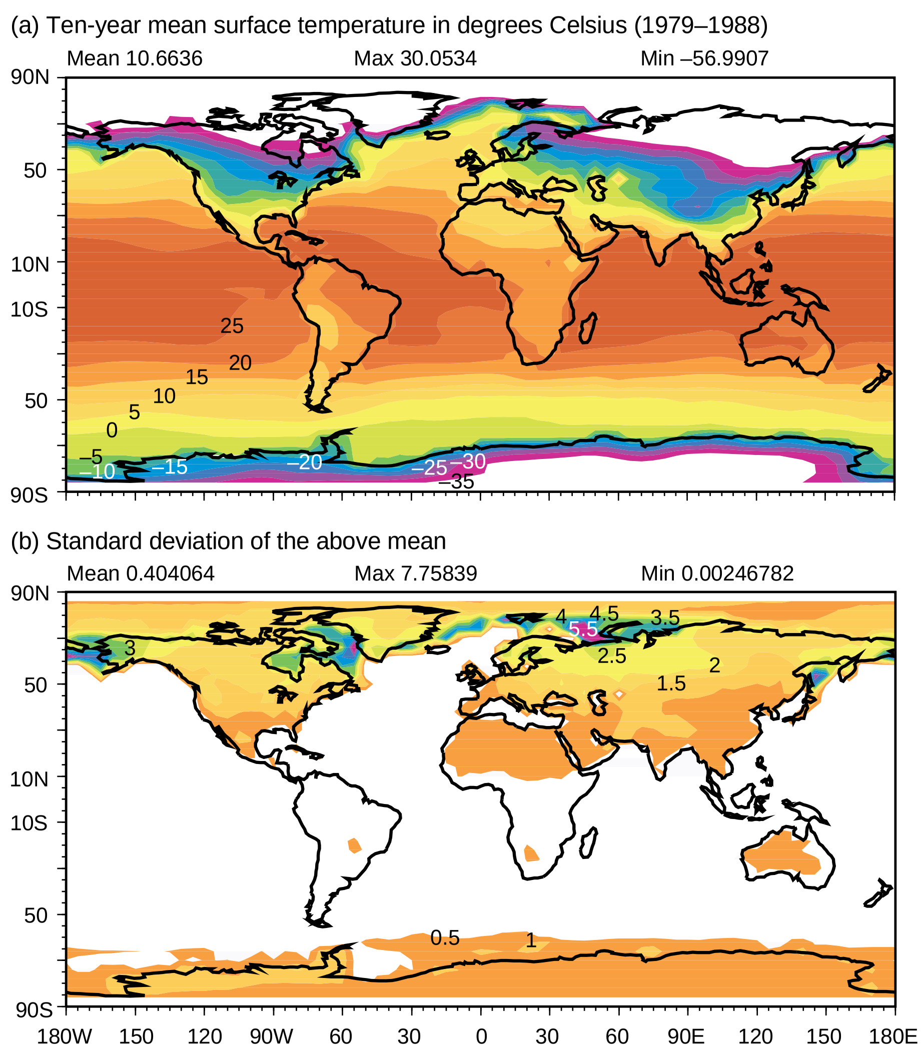

Figure 5. Temperature variability in the AMIP ensemble of 20 simulations. These maps show (a) the December–January–February mean surface temperature and (b) the variability as characterized by the standard deviation of the mean temperature. The standard deviation, not uniform over the globe, is largest in the extreme high latitudes, which are characterized by snow-covered land and sea ice.

Research Challenges

Progress toward a predictive understanding of global climate change depends on our ability to improve the computer simulations we use. This process is sometimes slow and occasionally controversial. The computer simulations are very complex because the processes that determine climate are nonlinearly coupled across a wide spectrum of space and time scales. For validation, we must rely on laboratory-scale experiments—which can shed light on isolated, individual processes—and on extensive field measurement programs to gather essential observational data. It is only with controlled simulations that we can explore the myriad "what if" scenarios.

One particularly important question that we now can address involves the predictability of the climate system. Short-term weather predictions are fundamentally limited by the chaotic behavior of the atmosphere: no matter how perfect the forecast model, the weather cannot be predicted beyond a few weeks. This is because even small errors in initial conditions—which are always present, because of limited precision and spatial resolution of observational data—are amplified by the turbulent nature of the atmospheric flow so that the statistical significance of the forecast is diminished after a few days.

We assume that the more general characteristics of climate can be predicted for considerably longer periods of time. However, the climate system may have very long time scales of natural variability, originating in part from the nature of large-scale ocean circulation patterns. In this context, it becomes difficult to discriminate between systematic effects (such as possible global warming) and low-frequency natural climate variations. Finding the limits of natural climate predictability in this sense is obviously a prerequisite to making useful predictions of possible anthropogenic effects. Experiments with fully coupled models, analogous to our ensemble work with the AMIP, are a first step in this direction.

We are also very interested in determining the possible impact of global climate change on scales of direct practical importance, on the order of tens to hundreds of kilometers (regional scales). It is on these scales that possible impacts on managed and natural ecosystem and water resources, for example, would be most apparent. This research is in a very early stage, but it will play an increasing role in the future. One approach that we will pursue is to use the global-scale climate model output to drive regional-scale models of hydrologic and ecological processesand thus capture local effects due to variations in topography, land use, and soil properties.

Such studies require world-class, high-performance computing capabilities, a multidisciplinary teamwork approach, and long-term institutional commitment. With new computing resources based on the knowledge we are gaining from collaborations such as ASCI, the Laboratory is positioned to continue making important and unique contributions to the science base of global climate research and to assist in the assessment of the consequences of potential climate change.

Key Words: Atmospheric Model Intercomparison Project (AMIP), carbon cycle, carbon dioxide, climate modeling, global climate, global climate model, greenhouse effect, massively parallel computers, sulfate aerosols.

Notes and References

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