Assessing Humanity's Impact on Global Climate

Capitalizing on strengths in computer modeling, Livermore researchers are working to provide policy makers a quantitative picture of our changing global climate.

EARTH returns the Sun's heat to space in the form of thermal infrared radiation. But atmospheric carbon dioxide (CO_2) and trace gases help keep our planet warmer than it otherwise would be by absorbing some of this radiation, thus blocking its escape. Human activities, especially the burning of fossil fuels, can intensify this natural greenhouse effect by pumping increased levels of CO_2 and other so-called "greenhouse gases" into the atmosphere.

Do these activities mean that our climate will become noticeably warmer, with a rate of warming (and accompanying changes to other climatic parameters like rainfall and sea level) great enough to harm human societies and natural ecosystems?

Other than waiting for the future to happen, the only means to answer this question is with computational modeling—specifically with general circulation models (GCMs) that simulate weather and climate in detail around the world. For something as complex as the climate system, these models are typically complex as well. These elaborate computer programs require the utmost in machine performance because they incorporate other state-of-the-art models of key physical processes affecting climate.

At Lawrence Livermore National Laboratory, we are applying computation expertise—originally developed to simulate nuclear explosions—to the challenging task of climate modeling. We also make use of Livermore expertise in atmospheric science that grew out of efforts to model fallout from nuclear explosion testing. These model-building and simulation efforts in climate studies are synergistic with other Laboratory programs, in that they all advance sophisticated techniques for programming simulation models on state-of-the-art computers.

While the increase of atmospheric CO_2 since the Industrial Revolution 200 years ago is apparent from geologic and instrumental records, it is not so obvious that a warmer climate has resulted (Figure 1). The Earth's surface has warmed slightly, on average, over the last century. So far, the increase is irregular and small, particularly when compared with GCM-based predictions of 21st century global warming, but not small compared to predictions of warming expected to date. The data also show that human production of CO_2 will not be the only factor in global temperature change.

Three Decades of Work

Global climate research has been a part of our work at Lawrence Livermore for three decades. (See *Energy & Technology Review*, September 1984, for a description of past work.) Today, we play a leading role in climate research, as is appropriate for a Department of Energy laboratory with missions that include studying the use of fossil fuels and their potential impact on global and regional environments.[1]

At Lawrence Livermore, our goal is to better understand global climate and humanity's impacts on it. Most of the Laboratory's global climate work is done in the Environmental Programs Directorate. The directorate's Atmospheric Sciences Division develops and applies climate models that represent key processes affecting the atmosphere, oceans, and biosphere. Using these complex models, we seek to improve scientific understanding of the mechanisms of global change in the environment and climate.

Our major climate research efforts are directed toward:

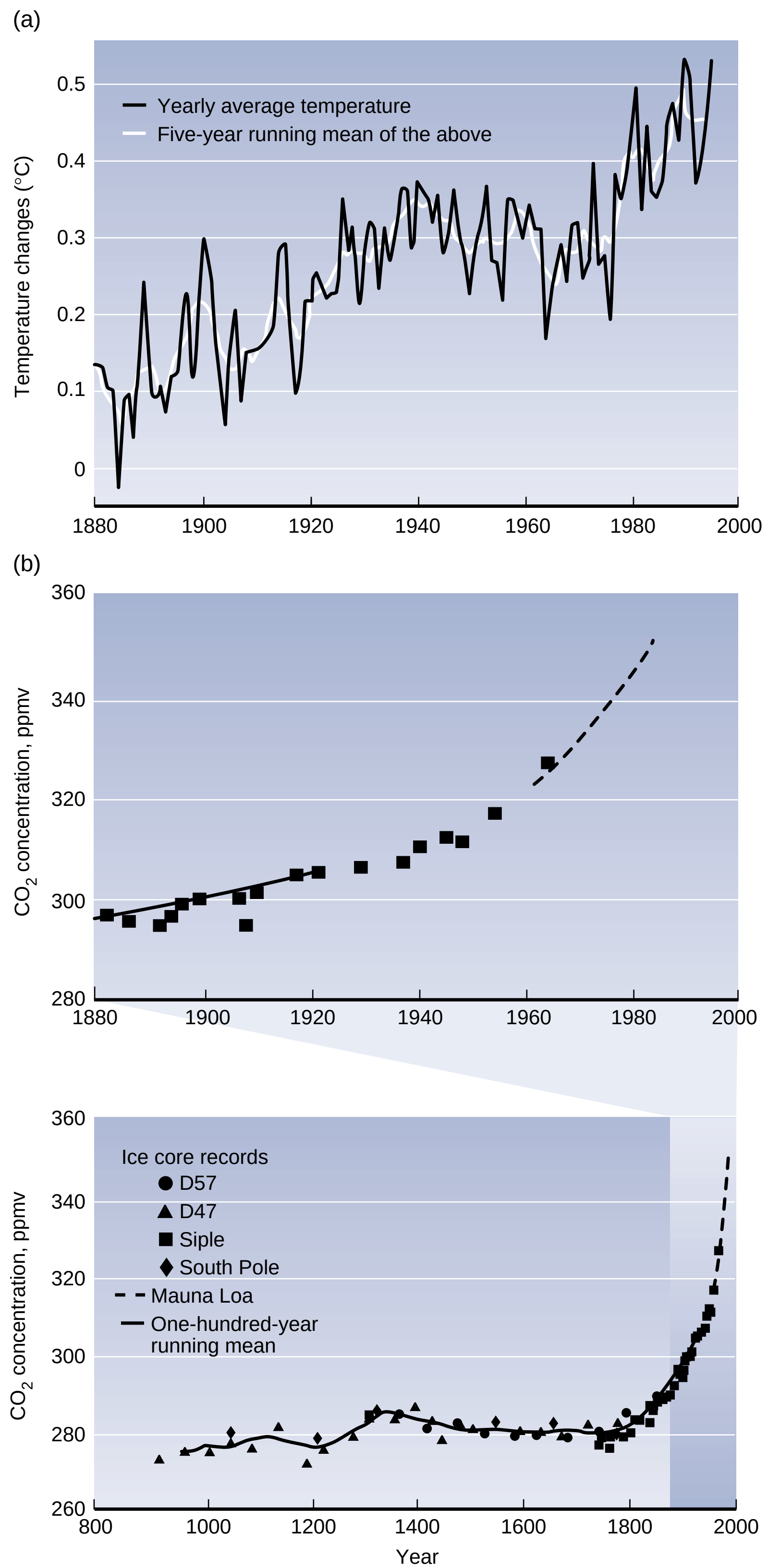
- Assessing the effects of aerosols.
- Modeling the carbon cycle.
- Applying advanced computing techniques.
- Finding the limits of climate predictability.

In these studies, climate researchers from other Laboratory areas are also involved, such as those in the Program for Climate Model Diagnosis and Intercomparison (PCMDI), who document climate model performance in order to reduce systematic errors (see box, p. 10).

Assessing Aerosol Effects

In recent years, we have been addressing the apparent disparity between the GCM predictions of global warming and the observational record. According to the models, greenhouse gases such as CO_2 should have raised average temperatures worldwide by 1°C during the past 100 years. Instead, temperatures climbed by about only half a degree, as shown in Figure 1.

One hypothesis to explain the disparity states that atmospheric sulfate aerosols might partially offset the



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.

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]

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,

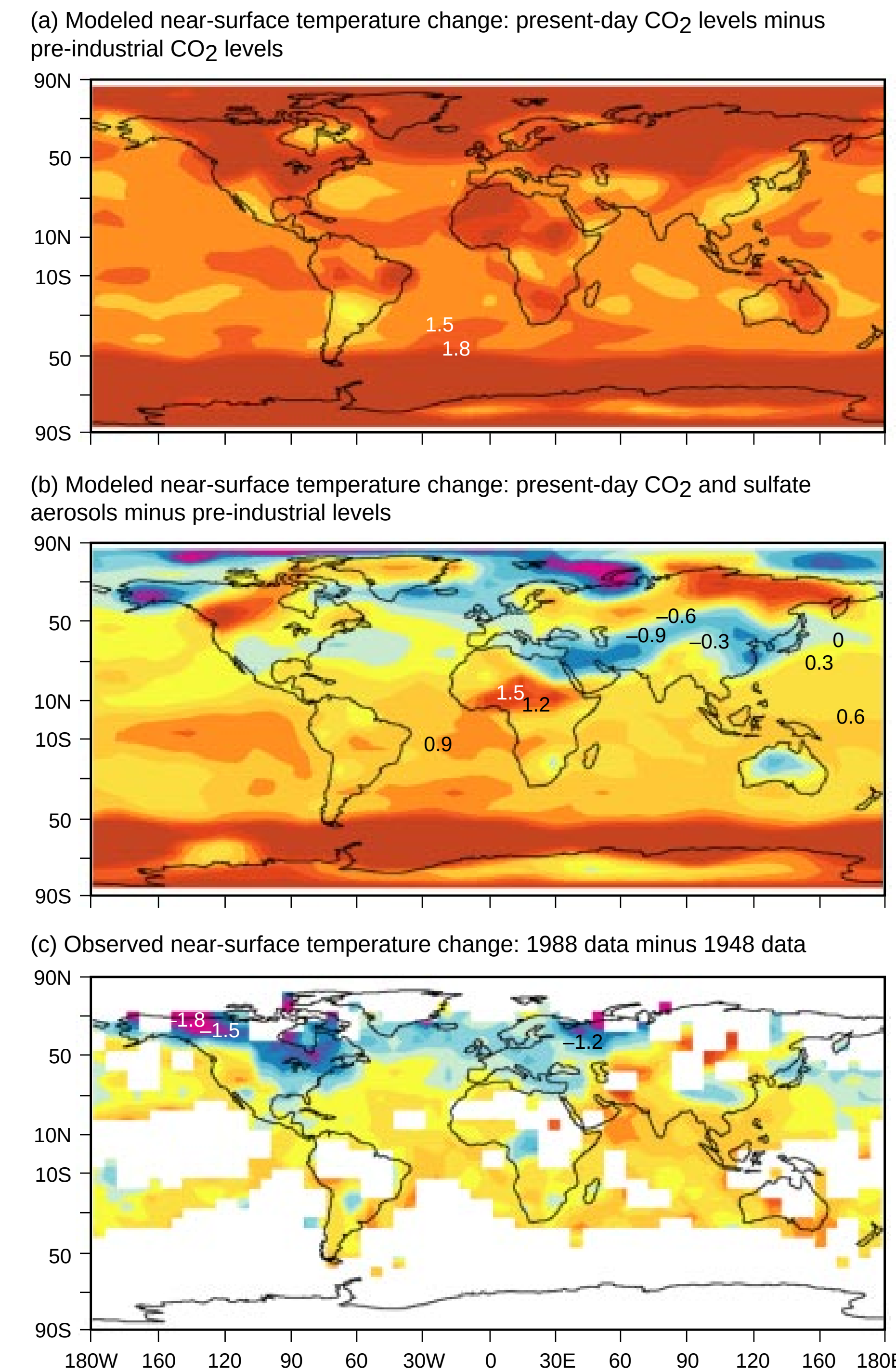


Figure 2. Temperature-change maps show that observed patterns of near-surface temperatures are in better accord with predictions from models that consider CO_2 and sulfur emissions than with models that consider CO_2 only. Notes: all temperature changes are for Sept., Oct., and Nov. in °C; white areas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

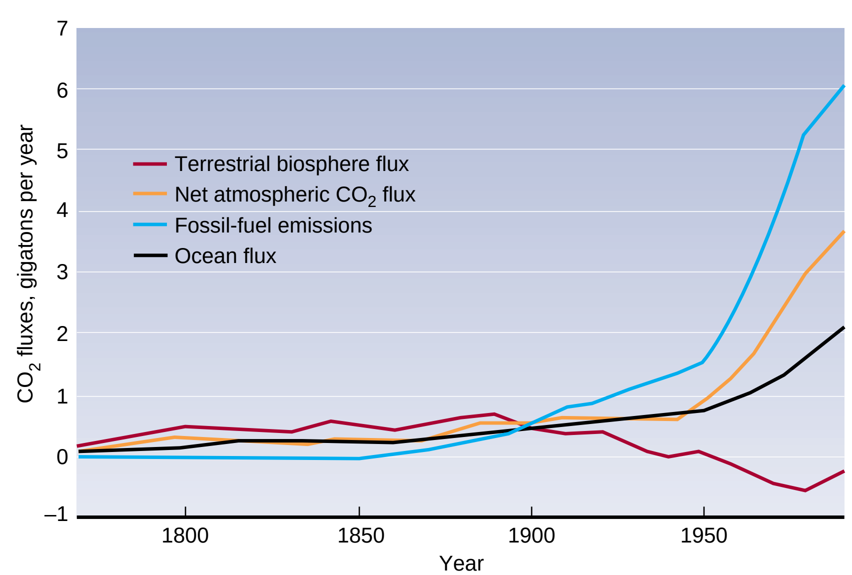


Figure 3. Carbon dioxide fluxes into and out of the atmosphere. The red curve shows that the terrestrial biosphere (plants and soils) was a net absorber of carbon from the atmosphere until about 1950. The observed yearly change in the carbon content of the atmosphere (gray line) is equal to the measured 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.

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.

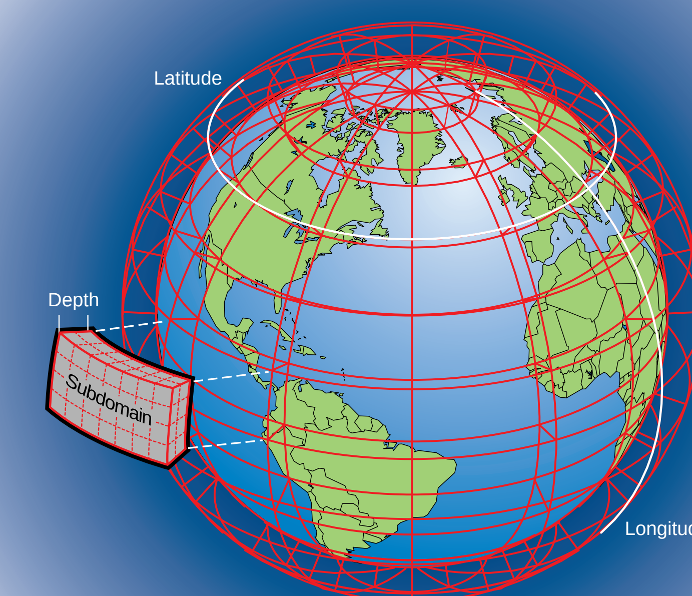
Applying Advanced Computing Techniques

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.

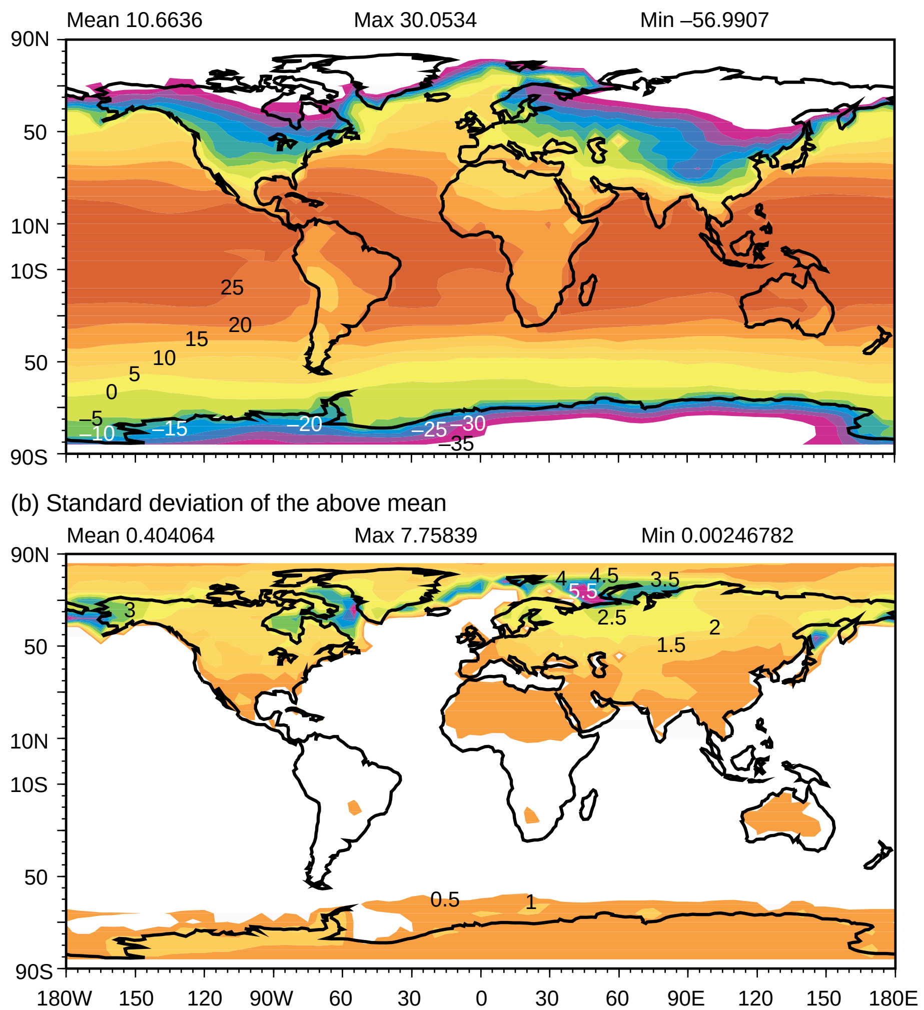


Figure 5. Temperature variability in the AMIP ensemble of 20 simulations. These maps show (a) the December–January–February mean surface temperature and (b) the variability as characterized by the standard deviation of the mean temperature. The standard deviation, not uniform over the globe, is largest 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.

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