

Developing for Predictive

The Community Climate System Model results from a multi-agency collaboration designed to construct cutting-edge climate science simulation models for a broad research community. Predictive climate simulations are currently being prepared for the petascale computers of the near future. Modeling capabilities are continuously being improved in order to provide better answers to critical questions about Earth's climate.

Climate change and its implications are front page news in today's world. Could global warming be responsible for the July 2006 heat waves in Europe and the United States? Should more resources be devoted to preparing for an increase in the frequency of strong tropical storms and hurricanes like Katrina? Will coastal cities be flooded due to a rise in sea level? The National Climatic Data Center (NCDC), which archives all weather data for the nation, reports that global surface temperatures have increased over the last century, and that the rate of increase is three times greater since 1976. Will temperatures continue to climb at this rate, will they decline again, or will the rate of increase become even steeper?

To address such a flurry of questions, scientists must adopt a systematic approach and develop a predictive framework. With responsibility for advising on energy and technology strategies, the DOE is dedicated to advancing climate research in order to elucidate the causes of climate change, including the role of carbon loading from fossil fuel use. Thus, climate science—which by nature involves advanced computing technology and methods—has been the focus of a number of DOE's SciDAC research projects.

Dr. John Drake (ORNL) and Dr. Philip Jones (LANL) served as principal investigators on the SciDAC project, "Collaborative Design and Development of the Community Climate System Model for Terascale Computers." The Community Climate System Model (CCSM) is a fully-coupled global system that provides state-of-the-art

computer simulations of the Earth's past, present, and future climate states. The collaborative SciDAC team—including over a dozen researchers at institutions around the country—developed, validated, documented, and optimized the performance of CCSM using the latest software engineering approaches, computational technology, and scientific knowledge. Many of the factors that must be accounted for in a comprehensive model of the climate system are illustrated in figure 1.

The Climate System

The first theoretical construct required for the study of climate is the principle of conservation of energy. Any energy that enters the system must eventually be removed for the principle of conservation to hold. This applies equally at various scales—from a small patch of ground, an entire ocean layer, or an astronaut's blue marble view of the Earth.

The Earth is a thermodynamic system, and climate serves as the energy flow process required to maintain equilibrium. The climate system achieves this stability by balancing energy input from the Sun with energy output via radiation from the planet's surface. For example, one job of the climate system is to transfer incoming energy from the sun-soaked tropics to the cold higher latitudes, where heat energy is radiated back out into space.

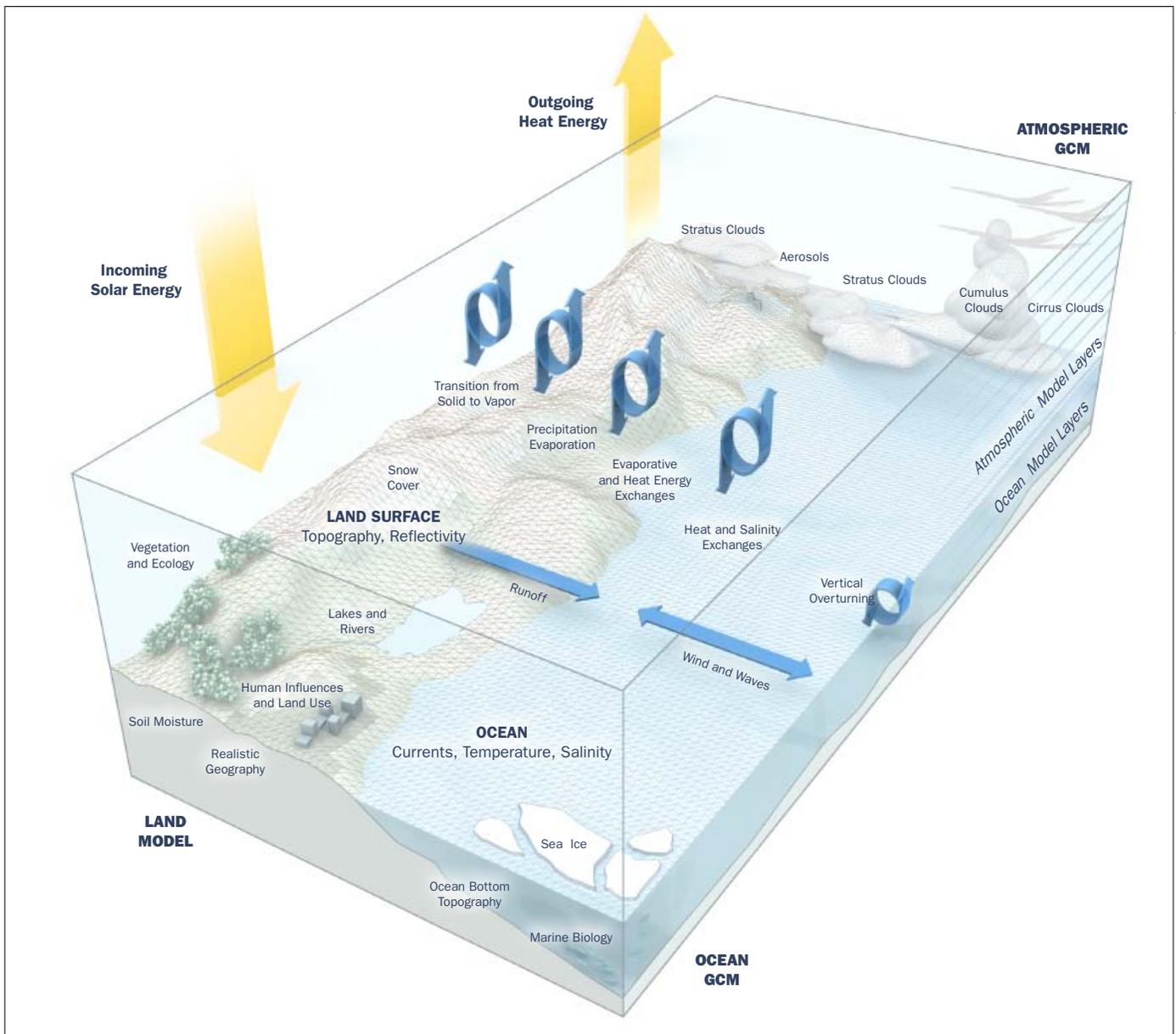
Components of the Earth's Climate

Wind patterns in the atmosphere such as Hadley cells (see sidebar "Wind Belts and Circulation

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MODELS

CLIMATE Science



BRYAN CHRISTIE DESIGN (BASED ON DATA AND GRAPHICS COURTESY OF NCAR)

Figure 1. The components of the Earth's climate system first interact vertically to establish a balance between the incoming solar energy and the outgoing heat energy that is radiated into space. The reflectivity of the Earth's surface (albedo) depends on vegetation type and whether the surface is land, lake, or ocean. The moisture and chemical content of clouds also change the reflectivity of cloud tops and the absorption spectrum for different wavelengths of light. The horizontal arrows in the diagram represent interactions involving the transport of material by winds, currents, and runoff. The atmospheric general circulation interacts with the ocean general circulation, each driving the other on a global scale.

Wind Belts and Circulation Cells

The prevailing wind belts encircle planet Earth, like broad bands of cloth wrapped around a sphere. The wind belts of the Northern Hemisphere (figure 2) include the Polar Easterlies, the Westerlies, and the Northeast Trade Winds. A similar set of wind belts—including the Polar Easterlies, Westerlies, and Southeast Trade Winds—can be found in the Southern Hemisphere.

Dividing the broad wind belts are narrow regions of rising or falling air, which are segments of Earth's circulation cells. The main circulation cells (figure 2) are the Hadley Cells, Ferrel Cells, and Polar Cells.

Each of these types of cells can be found in both hemispheres of the planet.

These systems of air movement are influenced by solar radiation and the Coriolis force—a result of Earth's rotation. For example, solar radiation is greatest at the equator. There, air at the surface of the planet warms and rises. The warmed air ascends into the troposphere and then flows towards both poles of the Earth. As the air cools, it begins to descend back to the surface, around latitudes 30 degrees north and south of the equator. Some of the air moves along the surface, towards the poles, creating the Westerlies. The

west to east movement of the Westerlies is caused by the Coriolis force. The rest of the cool, descending air moves back along the surface towards the equator, generating the Trade Winds. In their entirety, these patterns of air circulation make up the Hadley Cells located just north and south of the equator.

The wind belts and circulation cells are some of the factors that must be accounted for in modeling the broader, general system called climate. Because so many factors are involved, models of climate can be very complicated, and thus simulating such models generally demands a great amount of computational resources.

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Cells”) and ocean currents like the Gulf Stream are a combined product of the Earth's rotation and the unequal heating of the planet's surface. Winds and currents are the mechanisms that redistribute energy around the planet. These redistributions must abide by the physical laws of conservation of mass and momentum. For example, the chemical balance of gases in the atmosphere determines that incoming shortwave sunlight is absorbed and reflected longwave heat is trapped. The composition of gases and particulates in the atmosphere—including water vapor, carbon dioxide, methane, ozone, and aerosols—is determined by factors at the surface of the Earth, such as plant growth, soil properties, and human activities. Because of its reflectivity, ice also affects solar absorption and is an important feedback element in the climate system. The complexity of the interrelated factors is demonstrated in figure 1, which illustrates mass and energy exchanges among various climate system components.

Modern day climate models such as the third-generation Community Climate System Model (CCSM3) include the components shown in figure 1 into a detailed, first principles theoretical framework. SciDAC researchers supported by the collaborative endeavor of DOE, NSF, and NASA have worked to integrate this framework into computer code for use on powerful supercomputers. The CCSM project has bridged the gaps between disciplines, applying computer science to rigorous theory in order to develop practical scientific simulations.

Modeling Climate in Detail

Climate is often thought of as a weakly forced and strongly nonlinear dynamical system (sidebar “Dynamical Systems,” p48). The major factor forc-

ing the climate system is the solar constant ($1,367 \text{ W/m}^2$). Solar input variation—due to the sunspot cycle and the seasonal distance between the Earth and the Sun—are small, amounting to less than 4 W/m^2 . Increases in greenhouse gases in the atmosphere change the longwave absorption by an equivalent amount. The inherent nonlinearities of the system are evident in the constantly shifting weather patterns that arise from differential heating of the Earth's surface and instabilities of atmospheric flow. In terms of creating a reliable model, this means that fundamental physical laws must be treated carefully. Furthermore, factors such as process details, topography, bathymetry, and land use must also be considered. The resolution of the model must adequately represent all of these relevant dynamical interactions.

The nature of the climate problem and its dependence on what John Von Neumann called the “minutiae of computation” make qualitative arguments ineffective for developing predictive capability. The range of possible climate states and the variability of the Earth's weather are the result of rather complex feedback loops and balances among the system components.

As with many scientific endeavors that are simply not practical for the laboratory bench, computational experiments have emerged as the only reliable tools for developing verifiable, quantitative predictions. A reasonable explanation of the behavior of the climate system can result when simulation experiments are combined with careful validation and verification using observational data, such as from satellites and other tracking systems. However, without the theoretical basis expressed in the modeling framework, it would be impossible to develop predictive capability from such data alone.

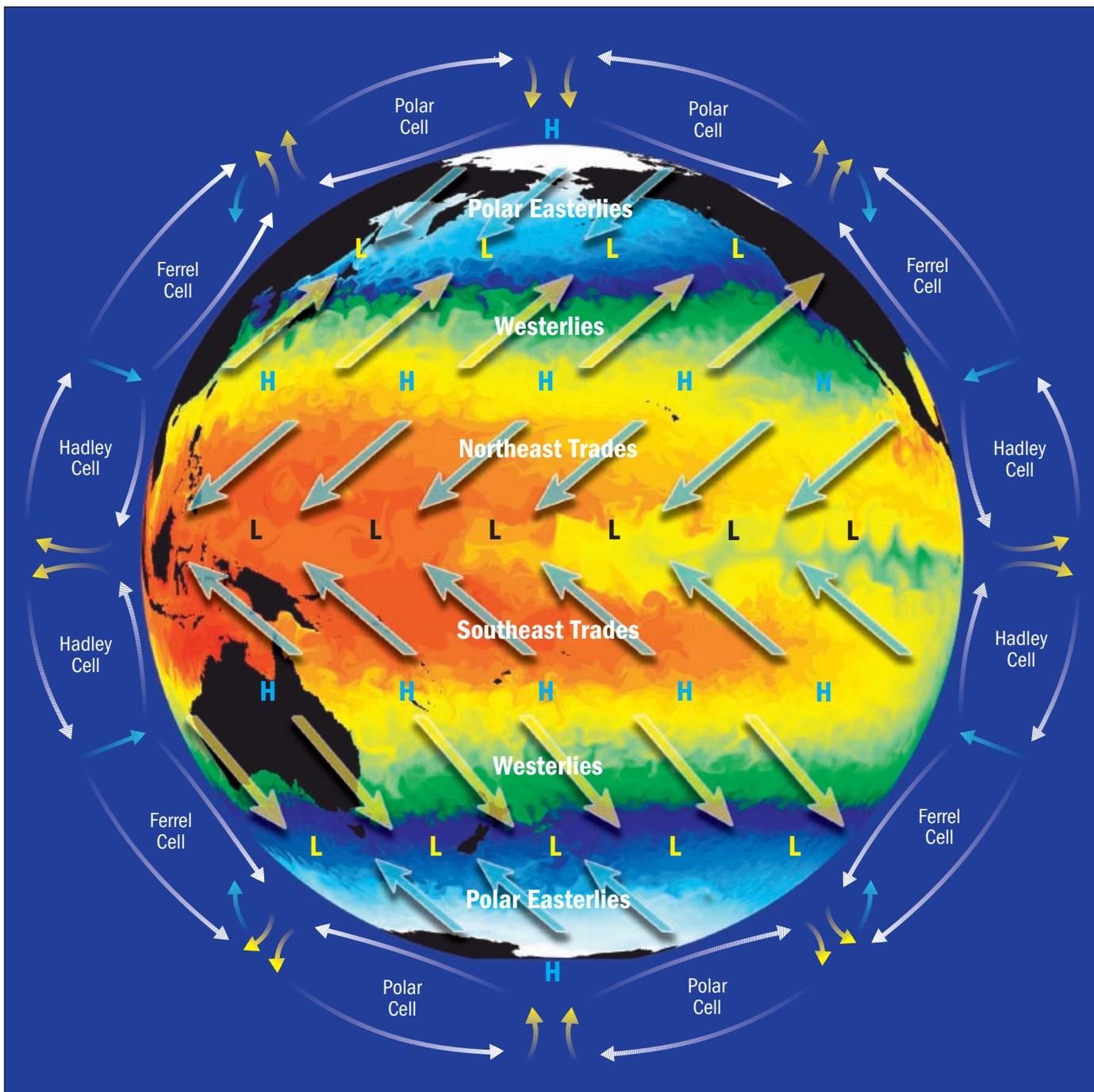


Figure 2. Shown here are the prevailing wind belts and primary circulation cells of the climate system on Earth. Patterns similar to those in the Northern Hemisphere also occur in the Southern Hemisphere.

Computational Methods

The development of new climate models is progressing at a rapid pace. The National Center for Atmospheric Research (NCAR) has been a major player in model development. At NCAR the component models have multiplied and the physical principles they represent have increased in complexity.

Resolution for atmospheric calculations has doubled twice in the last five years, with grid spacing reduced from 2.8° (300 km) to 1.4° (150 km),

and then down to 0.7° (75 km). This progression continues to benefit from weather forecast improvements at the European Center for Medium Range Weather Forecasting and other centers, where information-rich operational resolutions of 0.175° (20 km) are currently in use.

Like most scientific simulation projects, modeling the climate system is constrained by finite computing time resources. Thus, less informative resolutions are used for climate models than for weather models. In practice this amounts to

Dynamical Systems

Dynamical systems provide a way to describe mathematically how aspects of a scheme evolve, from one state to another, over time. Historically, the concept of dynamical systems developed from the study of the behavior of physical systems like planetary orbits, machinery, or molecules in a chemical reaction. A more modern application of dynamical systems is the recoding of data using encryption schemes or error correcting codes. Mathematically, a dynamical system can be manifested as either a function on a set or as a group of smooth curves tracking how states change. As a subject of mathematics, dynamical systems involve the long-term behavior and properties of systems like periodic orbits, equilibrium states, and sensitivity to initial conditions, as well as the emergence of local phenomena like invariant sets.

In this article, climate is described as a weakly forced and strongly nonlinear

dynamical system. Forcing of a dynamical system occurs when some external force is applied to the system. If the external force is strong compared to the internal interactions of the system, then the behavior of the forcing component will dominate the behavior of the system. However, if the system is weakly forced then the system will evolve with some mixture of the system's undisturbed behavior and the forcing behavior. For example, consider a tire swing hanging from a tree branch. Once set in motion, the swing will oscillate back and forth through the lowest point with some fixed frequency (no forcing on this example system). If a gentle wind is blowing, then the swing will oscillate but with some different frequency and at an angle (weak forcing by the wind component). If a very strong wind is blowing, then the rope would be pushed almost horizontally and

oscillate only slightly because of the wind (strong forcing by the wind component).

When dealing with a very complicated system, it is often convenient to approximate the system's behavior by considering a simpler system. For example, the behavior of linear ordinary differential equations is well understood and relatively easy to compute. Because linearity is an ideal rather than a realistic situation, it is useful to determine the types of systems that exhibit the behavior and properties of linear systems. Systems that do not have the simplicity of their linear counterparts are called strongly nonlinear. Strongly nonlinear systems, like climate models, are more difficult to work with because they are computationally expensive and require some knowledge of system behavior *a priori*.

Contributor: Nick Long

trading some spatial accuracy for the ability to make projections on very long time scales. For example, weather forecasting involves trends specific to small spaces over short periods of time, such as the next few days or weeks. Climate modeling, on the other hand, deals with large trends over time periods of decades, centuries, or longer. Hence, some spatial accuracy can be sacrificed in order to make long-term climate simulations computationally practical.

Of course, this tradeoff inhibits the ability to provide information for regional climate projections, and so there is always a demand for increased resolution in climate simulations. In fact, many physical processes are inadequately represented at current resolutions. In one such example of using higher resolution, simulations using the Parallel Ocean Program (POP2) have been carried out by SciDAC investigators and their collaborators at resolutions of 0.1° and greater. This permits simulated ocean eddies to form and transport heat in much the same way as observed in the actual ocean.

Additionally, a new algorithm for atmospheric flow is experiencing wider use within the modeling community. The new method involves a flux-form semi-Lagrangian formulation and a finite-volume discretization of the spatial extent. This algorithm replaces the Eulerian and semi-Lagrangian spectral dynamical cores of the Community Atmospheric Model that were used for the Intergovernmental Panel on Climate Change

(IPCC) simulations (sidebar “Intergovernmental Panel on Climate Change,” p49). The improved version uses a special technique called the Piecewise Parabolic Method (PPM) to construct fluxes in a vertical coordinate. Since this method is strictly conservative, it has been the method of choice for an increasing number of scientists interested in atmospheric chemistry, aerosols, ozone, and carbon dioxide distributions.

Efficient implementation of traditional methods as well as novel numerical techniques has dramatically boosted the productivity of scientists using the CCSM and its component models. Programming practices adopted from software engineering have led to logistical improvements—making the models maintainable, easily extensible, and portable across a wide variety of computing equipment while maintaining high computational performance.

Planning for Petascale Computing

The challenge represented by the exponential growth in computing capability is entering a new and exciting chapter. Scientists are preparing to utilize a computer—planned to be available in 2009—with 25,000 to 100,000 processors delivering a petaflop of computational power.

In theory, petascale machines can perform 1,015 floating point operations per second, but software tools run on such machines must be designed specifically to exploit the awesome power of the hardware. The current approach to

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Intergovernmental Panel on Climate Change

Starting in February 2007, the Intergovernmental Panel on Climate Change (IPCC) began release of the Fourth Assessment Report of the scientific, technical and socio-economic information relevant for understanding climate change, its potential impacts, and options for adaptation and mitigation. SciDAC program efforts have enabled scientific discovery that is contributing directly to the science and policy discussions surrounding the IPCC reports.

The scientific basis of the report is partly grounded in the collaborative efforts by SciDAC-sponsored researchers to develop advanced

climate models, produce high-end simulations using supercomputers, and provide the infrastructure needed for the international scientific community to share model results. In particular, the Community Climate System Model (CCSM) was used for a substantial portion of the U.S. modeling contributions. CCSM is the subject of a SciDAC model development project. The scenario simulations were performed at relatively high resolution in ensemble mode using computing resources from NCAR, DOE's National Energy Research Scientific Computing (NERSC) center (see "Science-Driven Supercomputing,"

p36), the ORNL National Center for Computational Sciences (NCCS), and the Japanese Earth Simulator Frontier Center. Data from the CCSM simulations as well as the other international modeling centers are available through the SciDAC-sponsored Earth Systems Grid Project located at the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI), located at LLNL.

Contributor: Dr. John Drake, ORNL

Download the IPCC report at: <http://www.ipcc.ch>

parallel computing in the CCSM is based on two principles: (1) decompose the data structure of each component to provide parallel throughput, and (2) remap fields from one data structure to another as needed. Until recently little work has been done on parallel algorithm design factors, such as maintaining good load balance, scaling to large processor counts, or minimizing overall communication costs. Generally, the parallel implementations of the past few years have fit well with available supercomputers, which are based on powerful vector or server architectures tightly linked with high speed networks. Unlike these machines, the next generation of petascale computers will be designed to utilize a staggering number of relatively weak processors coupled together with slow networks. Computers of this architecture are more sensitive to task scheduling, load imbalance, and hardware failure, and thus require new approaches and careful software design.

SciDAC-sponsored computer science research has led to tools and techniques critical to tackling the petascale challenge. In order to deal with larger quantities of output, the Scientific Data Management project (*SciDAC Review*, Fall 2006, p28) generated a powerful input/output tool called Parallel NetCDF. New software component technologies for coupling parts of a computation—like the Common Component Architecture (CCA) project—as well as performance monitoring tools are available for measuring how each processor is coping with the load assigned to it. Development continues on new system tools for scalable operating systems. New mathematical techniques from the Terascale Optimal PDE Simulation (TOPS) project (*SciDAC Review*, Spring 2006, p50), such as the Newton–Krylov methods and the discontinuous Galerkin discretizations, are also being prototyped with new

grid systems from the Terascale Simulation Tools and Technologies (TSTT) project. These advances are being set up for use in atmospheric and ocean flow problems. Overall, the SciDAC program has spawned a rich network of expertise and an infrastructure of methods and technology that will help advance climate modeling to the new levels made possible by petascale computing.

It might seem logical that increasing the number of available processors by a factor of ten equates to running ten times as many jobs simultaneously. Although this obvious parallelism would help improve the statistical information from ensemble forecasts, current work is focused on exploiting the increased processing power for more comprehensive modeling of the climate. The computational cost of the simulation grows as additional features—such as robust atmospheric chemistry, ocean ecosystems, and dynamic land vegetation—are added to the model. A coupled global Earth system model would simulate important factors such as changing soil and ocean carbon pools that may influence the long-term balance of carbon dioxide in the atmosphere. An increasing focus on the regional impact of climate change will also require higher resolution models. While this is an obvious scaling opportunity for new architectures, new computational methods will be required to address the resulting time-step constraints for century-scale simulation. The new DOE computer platforms and SciDAC algorithm development will make such advances possible as the challenge shifts to understanding and utilizing new climate simulation results.

Results—What the Models Predict

Climate involves weather averaged over time combined with statistics accounting for the

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Ocean Modeling and the Interaction of Ocean Ecosystems

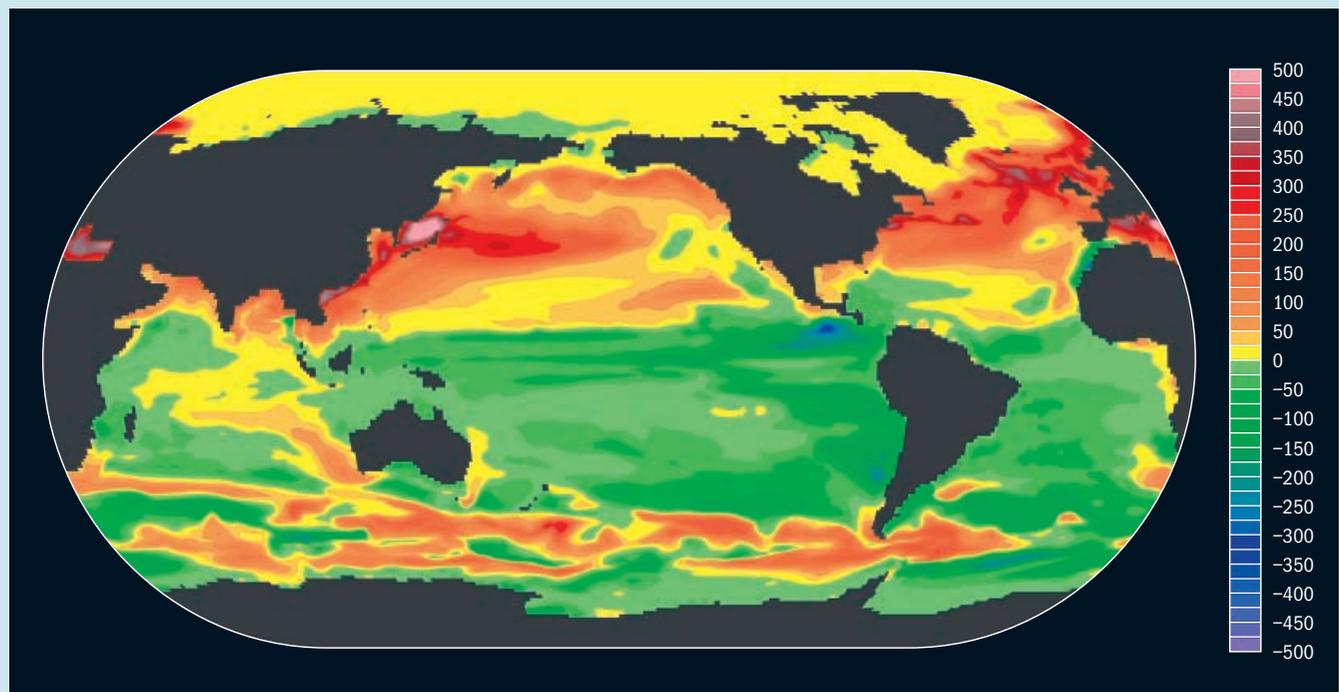


Figure 3. Carbon dioxide gas flux (in tonnes/km²/year) between the ocean and atmosphere averaged over December of year 9 of the fully coupled biogeochemistry simulation. Positive values indicate uptake by the ocean; negative values indicate out-gassing into the atmosphere. The ocean uptake in the Southern Ocean is due to a phytoplankton bloom.

Oceans are an important component of the climate system, transporting up to 50% of the heat from equator to poles. This heat transport is a result of a global thermohaline or “conveyor belt” circulation, driven by density changes as warm water cools (thermo-) and becomes saltier (-haline) due to evaporation and ice formation in regions like the North Atlantic Ocean.

At the surface, this circulation is manifested in current systems like the Gulf Stream that transport warm water northward, moderating the climate of Europe and melting sea ice. Detailed topographic features and the dynamics of ocean eddies at small spatial scales (20–50 km) help to determine the location of these current systems; high

resolution simulations (0.1°) are required to adequately represent them. Such ocean simulations have been undertaken by scientists at LANL and their collaborators at the Scripps Institute for Oceanography and the results have been in good agreement with satellite data and other observations.

A simulation with a high resolution ocean coupled to sea ice, land, and atmosphere components is currently being configured and will be completed over the next year. This will demonstrate the improvement to climate simulations possible when ocean currents are more accurately represented.

The ocean is also a major sink of carbon dioxide in the global carbon cycle. Ocean organisms like phytoplankton take up carbon

dioxide through the process of photosynthesis and sequester it in the ocean for long time periods. Ocean organisms also emit dimethyl sulfide (DMS) and are one of the largest natural sources of aerosols that affect cloud formation and irradiative balance in the atmosphere. To examine how the ocean takes up carbon and emits DMS, an ocean ecosystem model and a trace gas model developed under SciDAC were added to the physical ocean model. This ocean biogeochemical model was subsequently coupled to an atmospheric chemistry model, exchanging carbon dioxide and DMS fluxes. The prototype Earth System Model was run for 9 years and the uptake of carbon in the ocean is illustrated in figure 3.

frequency of extreme conditions. It makes sense to talk about the climate of the mid-century—a broad trend which we have some hope of being able to predict—but it is impossible to forecast the exact weather in 2056.

A standard exercise in climate prediction is to project possible outcomes for the last decade of the 21st century based on projected greenhouse gas emissions. For a medium range emission scenario,

the CCSM3 predicts a warming of 1.1 °C by mid-century and 2.3 °C by the end of the 21st century. The warming is accompanied by other results. A 25 cm rise in sea level has been predicted. The North Atlantic conveyor belt-like circulation (sidebar “Ocean Modeling and the Interaction of Ocean Ecosystems,” p50) will slow by about 24%, but the model indicates that, if carbon dioxide levels are stabilized, the circulation pattern will recover over

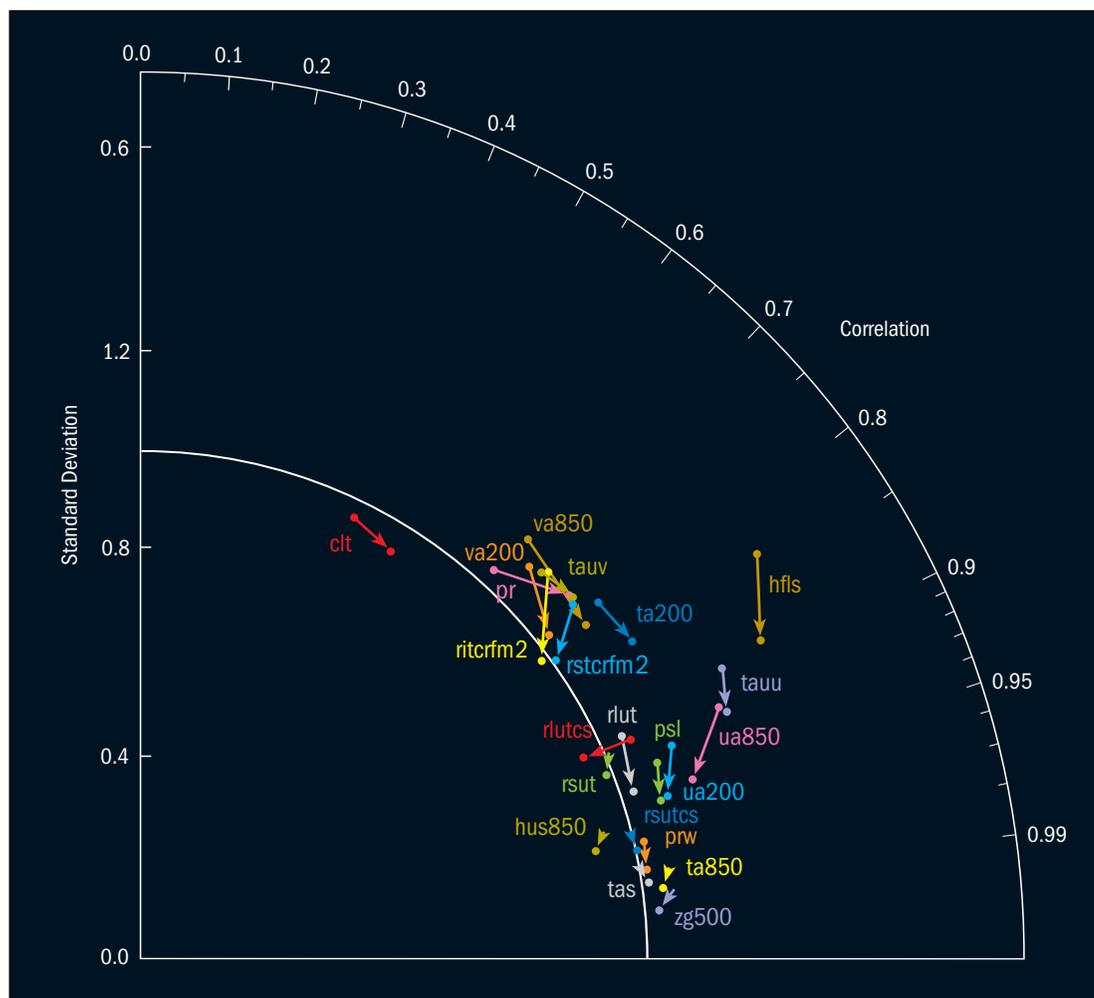


Figure 4. Taylor diagrams for the finite-volume General Circulation Model (fvGCM) model (the arrows go from the 2 x 2.5 to the 0.4 x 0.5 resolution version) compared to observations over the period 1979 to 1999. This test is defined as part of the Atmospheric Model Intercomparison Project (AMIP) sponsored by the DOE Climate Change Prediction Program. This study information was provided by Dr. Phil Duffy of LLNL.

the following two centuries. Most temperature changes will occur in the high latitudes near the poles while the mid-latitudes will likely experience more moderate temperature increases. An El Niño-like response to the warming will provoke increased precipitation in the tropics and mid-latitudes but a decrease in the subtropics. Precipitation from monsoon rains will increase. The model results show no significant soil drying in the Northern Hemisphere mid-latitudes. Rainfall will typically be heavier throughout the year but this factor will be offset by reduced winter snowfall. Warmer temperatures should lead to greater evaporation from the soil, and thus late summer soils will tend to be drier at the end of the 21st century, relative to the present.

A key unknown deals with what will happen to the polar caps and ice sheets. Model predictions indicate that the caps and ice sheets will become increasingly vulnerable to melting from below during the summer as the North Atlantic sea temperatures rise and the circulation pattern slows

and lengthens. Melting ice sheets are only now being added to models as observations indicate the Greenland and West Antarctic ice sheets may be melting more rapidly than previously realized. Adding important factors like this melting phenomenon is an example of why the models must be continuously updated and prepared for simulations on more powerful computers.

Verifying Models—Confidence Levels

To determine the validity of new climate models, two simulations are subjected to close and careful scrutiny. The first verification test is a control simulation that fixes the boundary conditions and runs for several centuries. This simulation tests the equilibrium of the model and yields information concerning the “drift” and stability of the model. It also checks the balance of processes, like poleward heat transport, and provides a comparison with observed climatology.

The second simulation test compares historical climate data with the simulated climate generated

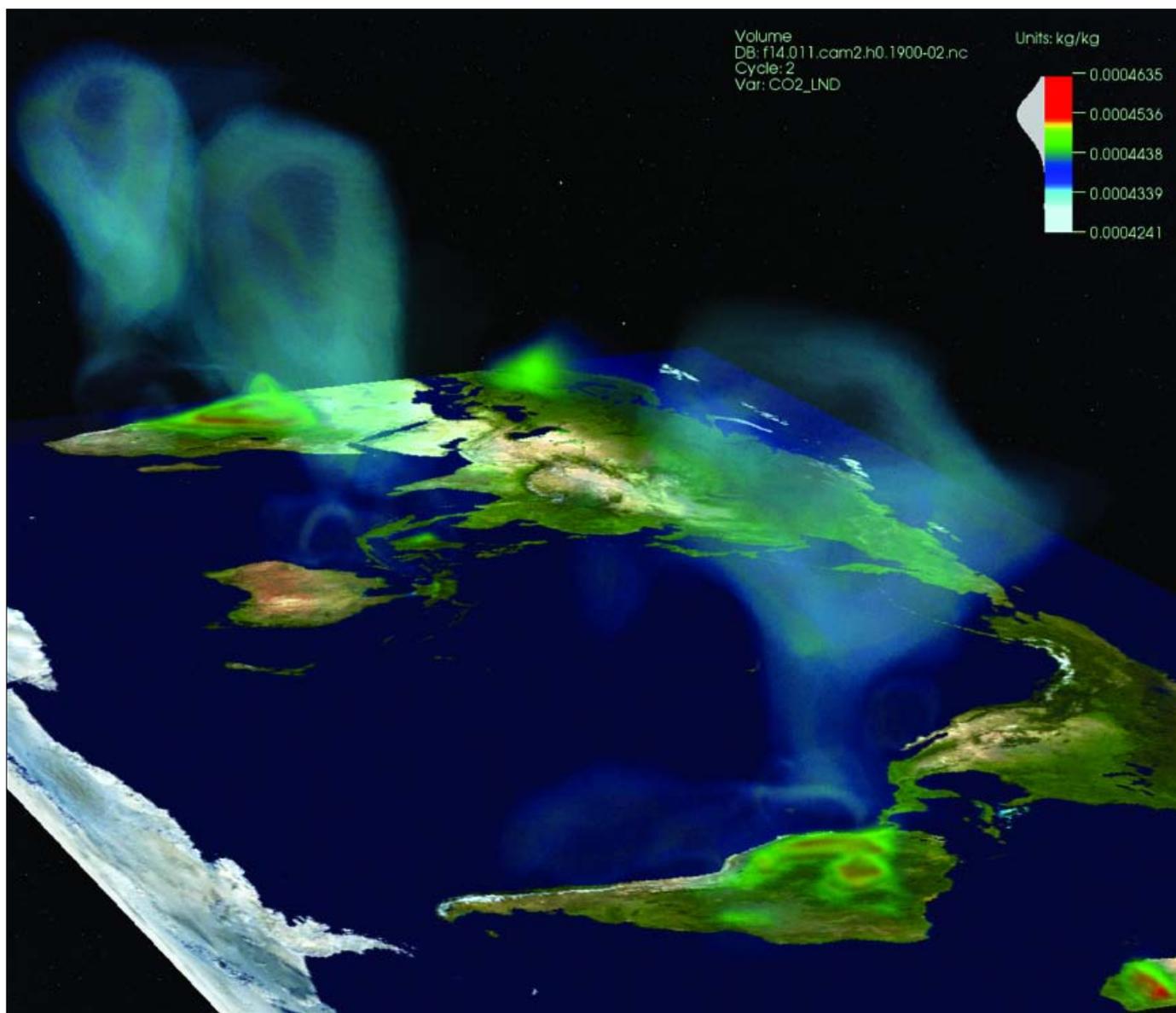


Figure 5. A snapshot of the simulated time evolution of the component of atmospheric carbon dioxide (CO_2) concentration originating from the land surface for February 1900. This “green CO_2 ” is a product of the net ecosystem exchange (NEE) and the CO_2 flux due to respiration of vegetation (autotrophs) and soil microbes (heterotrophs) minus that taken up for ecosystem production. CO_2 is transferred as NEE from the Community Land Model Version 3 (CLM3)—coupled with the CASA’ terrestrial biogeochemistry model—to the Community Atmosphere Model (CAM3), where it is advected as a tracer throughout the troposphere. The underlying simulation is one of a number of transient runs performed for Phase 1 of the Coupled Climate/Carbon Cycle Model Intercomparison Project (C4MIP) using the Community Climate System Model (CCSM) on the Leadership Computing Facility (LCF) Computational Climate Science End Station (CCSES; Dr. Warren Washington, Principal Investigator). These CCSM simulations were run on the Cray X1E in the National Center for Computational Sciences (NCCS) at ORNL. Information about this study was provided by Dr. Inez Fung (LBNL), Dr. Jasmin John (University of California—Berkeley), and Dr. Forrest Hoffman (ORNL).

by the model. The model is forced in a time-dependent fashion with actual atmospheric carbon dioxide concentrations, solar variability, and dust from volcanic eruptions. Satellite and weather station data are used to identify where improvements need to be made.

The moment of truth in any modeling project comes when the final version of the model is compared with observations. Figure 4 depicts a Taylor diagram, a specialized graph used for communicat-

ing these comparisons between model and empirical data. More than twenty output fields are measured and correlated with observational data using standard deviation as a measure. If an arrow points toward zero on the Taylor diagram, the deviation of the output has been reduced and the correlation has improved, that is increased from one version of the model to the next. The diagram in figure 4 compares a low resolution model to a high resolution version of the Community Atmosphere Model

Land Carbon–Climate Interactions and the C-LAMP project

The terrestrial simulation modeling component combines the biogeophysics of the Community Land Model version 3 (CLM3) with the Carnegie and Stanford Approach (CASA) biogeochemical model of Randerson, modified for use in global climate models. This modified biogeochemical module, called CASA', was formerly integrated into the Climate System Model Version 1.4 (CSM1.4) and used for a 1,000-year simulation as well as a variety of climate change simulations that were recently described.

CASA' simulates the life cycles of CLM3's plant functional types from carbon assimilation via photosynthesis to mortality and decomposition, and the return of carbon dioxide to the atmosphere via microbial respiration. There are three vegetation (live) carbon pools and nine soil (dead) pools, and the rates of carbon transfer among the pools are climate sensitive. The carbon cycle is

coupled to the water cycle via transpiration and to the energy cycle via dynamic leaf phenology and its effect on albedo—a measure of reflectivity. A terrestrial carbon dioxide fertilization effect is possible in the model because carbon assimilation via the Rubisco enzyme is limited by internal leaf carbon dioxide concentrations, eventually saturating at high carbon dioxide concentrations.

In the CASA' formulation, net primary productivity (NPP) is assumed to be 50% of gross primary production (GPP) as calculated by CLM3. NPP is allocated to the three live pools (leaf, wood, and root) with preferred allocation to roots under water-limited conditions and to leaves under light-limited conditions. Turnover times of the three live pools are specific to each plant functional type, and the leaf mortality of deciduous trees includes cold-drought stress to cause leaf-fall in one or two months. Leaf biomass is

translated into prognostic leaf area indices (LAI) using specific leaf areas (SLA) so that LAI varies with climate. Excess carbon above the limits placed on LAI is added to litter fall.

For the nine dead carbon pools, leaf mortality contributes to metabolic and structure surface litter, root mortality contributes to metabolic and structure soil litter, and wood mortality contributes to coarse woody debris. The subsequent decomposition by microbes leads to transfer of carbon to the dead surface and soil microbial pools as well as to the slow and passive pools. A fraction of each carbon transfer is released to the atmosphere via microbial or heterotrophic respiration. The rates of transfer are climate sensitive and are functions of soil temperature and soil moisture averaged over the top 30 cm of soil. More information and an image from a relevant simulation can be found in figure 5.

(CAM) with the finite volume dynamical core. It can be concluded that increasing the resolution resulted in significantly better predictions for some fields while only marginally improving others.

Summary and Future Directions

The questions being asked of the modeling community may be shifting from “Is climate change occurring?” to more quantitative “When?” and “How?” inquiries. To accurately address these questions and provide the best scientific groundwork for policy makers, many of the known deficiencies with coupled climate models must be fixed.

Variations in the path of the Gulf Stream and other current systems need to be tracked to better predict heat transport, deep water formations, and melting under sea ice and ice sheets. Indeed, the CCSM needs to add a component for the world's ice sheets before studies of rising sea level and rates of glacial accumulation and calving are theoretically grounded. In the atmosphere, precipitation must be brought more into line with geographic distributions so that soil moisture levels will be realistic and the right plants can grow in the right places. The coupling of ocean and atmosphere that give rise to oscillations like El Niño and the Pacific Decadal Oscillation (PDO) must also be improved. There is also hope that by including carbon and aerosol chemistry in the coupled model, the carbon cycle can be better quantified, understood, and predicted.

The next generation of models will earn the title “Earth system models.” This is, in fact, a major charge of the new SciDAC-2 project “A Scalable and Extensible Earth System Model for Climate Change Science,” led by PI Dr. John Drake (see “SciDAC-2: The Next Phase of Discovery,” p16). Supported by two Science Application Partnerships (sidebar “Science Application Partnerships,” p21), this new project aims to construct a first-generation Earth system model that fully simulates the coupling between the physical, chemical, and biogeochemical processes in the climate system. The broad web of investigators will build upon CCSM3 and looks forward to developing CCSM4 in time for the arrival of petascale machines planned for 2009.

The complexity of a new model, the consequent computer code, and the petascale simulation platform all present a great challenge to the scientists involved. Aside from the issues of scalability, researchers are also faced with a scarcity of data to validate biological responses and interactions within the climate system. The first Earth system model may not contain all possible and desired processes, but it marks an important beginning—the building of a solid base that will lead to scientific discovery. ●

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Further Reading

CCSM
<http://www.cesm.ucar.edu/>