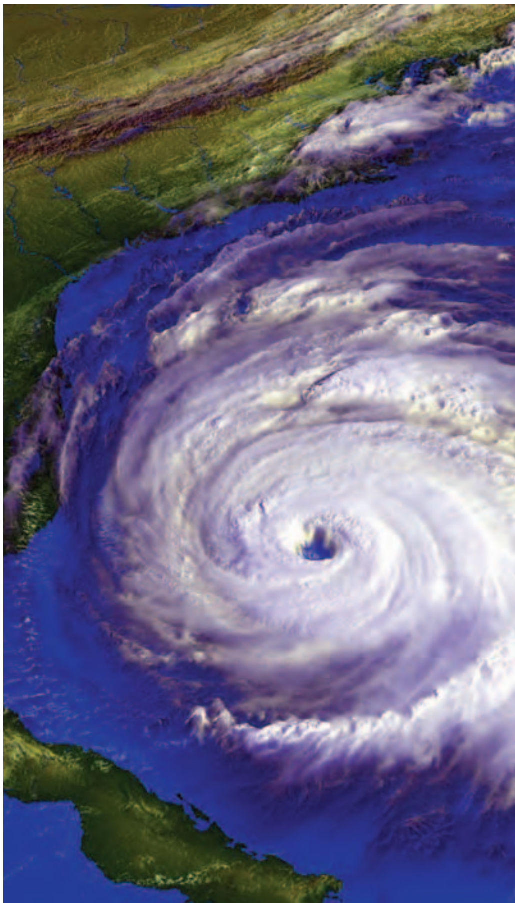


2 | Climate Variability and Change

Strategic Research Questions

4.1 To what extent can uncertainties in model projections due to climate system feedbacks be reduced?
4.2 How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?
4.3 What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?
4.4 How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?
4.5 How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?

See Chapter 4 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

CCSP-supported research has made significant advances in understanding the causes of climate variations. Substantial progress has also been made in incorporating this new knowledge into frameworks for predicting future climate variability on seasonal-to-interannual time scales and for projecting the potential climatic consequences of human activities.

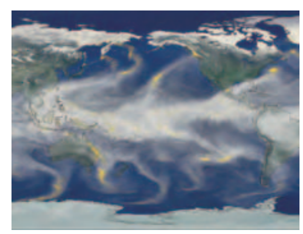
Scientists are increasingly aware that climate fluctuations occurring at a variety of time scales are intrinsically linked. For example, future variability of El Niño and its associated global climatic impacts are likely to depend partly on how average conditions of the ocean-atmosphere system change with time. A coordinated research strategy is essential to address scientific questions associated with both short- and long-term climate variations. The climate variability and change (CVC) research component of the *CCSP Strategic Plan* provides this strategy. It describes an ambitious, coordinated set of activities that builds on recent advances and is framed by two broad and important questions:

- How are climate variables that are important to human and natural systems affected by changes in the Earth system resulting from natural processes and human activities?
- How can emerging scientific findings on climate variability and change be further developed and communicated in order to better serve societal needs?

Current CVC research is addressing the five strategic research questions listed at the beginning of this chapter, which reflect the research approaches, milestones, products, and payoffs described in the *CCSP Strategic Plan*.

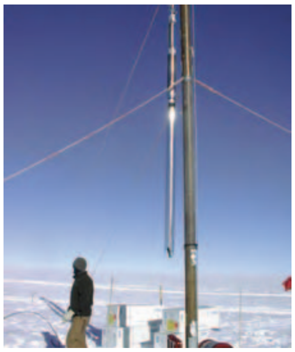
Making progress toward these objectives requires close cooperation among a variety of disciplines. In some cases, virtually all of the scientific elements encompassed by the CCSP agencies must come together to jointly address these challenges. The research highlights presented here provide a sampling of the breadth encompassed by the CVC component of CCSP over the past year.

Highlights of Recent Research



Selected highlights of recent CVC research supported by CCSP participating agencies follow.

Ancient Climate of the Western United States.[1,19] Evidence indicates that the climate of northern California over the past 3,500 years has been dominated by El Niño cycles. Paleoclimatologists infer this from the width of annual growth rings of redwood trees, the contents of packrat middens (debris piles), and the chemistry of tiny planktonic foraminifera (shelled, single-cell organisms preserved as fossils in the geologic record). In addition, these scientists concluded that abundance variations in the planktonic foraminifer *Globigerinoides sacculifer* in marine cores from the western and northern Gulf of Mexico can serve as an effective proxy for the southwestern U.S. monsoon on millennial and sub-millennial time scales. The marine record confirms the presence of a severe multi-century drought centered at approximately 1,600 years before present, as well as several multi-decadal droughts that have been identified in a long tree-ring record spanning the past 2,000 years from west-central New Mexico. The marine record further suggests that the southwest monsoon circulation, thus summer rainfall, was enhanced in the middle Holocene (approximately 6,980-4,710 years before present). The marine proxy record provides the potential for constructing a highly resolved, well-dated, and continuous history of the southwest monsoon for the entire Holocene (approximately the last 10,000 years). Records of U.S. paleoclimate such as those described above provide measures of natural variability and a context for attributing the causes of recent climate change.



Borehole Climate Reconstructions Show 500-Year Warming Trend.[18] A new analysis indicates that the average temperature of the Northern Hemisphere has increased by 1°C since A.D. 1500. This estimate is somewhat greater than Northern Hemisphere temperature reconstructions based on most inferences from tree and ice cores. Vertical temperature profiles obtained from 695 boreholes were used to make this estimate. Boreholes can be used to infer past temperatures because temperature changes at the surface affect the subsurface temperature. These subsurface changes slowly propagate downward, so that temperatures farther underground correspond to temperatures farther back in time.

***North American Drought Atlas* Indicates Increased Dryness during the Medieval Warm Period**.[6] Analyzing paleoclimate records in the western United States over the past 1,200 years, scientists found evidence that elevated aridity in the U.S. West may be a natural response to climate warming. The study revealed that a 400-year-long period of elevated aridity and epic drought occurred in what is now the western United States during the period A.D. 900-1300. This corresponds broadly to the so-called "Medieval Warm Period," a time in which various paleoclimate records indicate unusual warmth over much of the Northern Hemisphere. The study's authors used tree ring records to reconstruct evidence of drought, and also examined a number of independent drought indicators ranging from charcoal in lake sediments to sand dune activity. The team then used published climate model studies to explore mechanisms that link warming with aridity in the western United States. The authors of the new study postulate that certain mechanisms associated with warming may lead to increased prevalence of drought in the western interior region of North America. A CD-ROM summarizing the data, called the *North American Drought Atlas*, is available through the web site <www.ngdc.noaa.gov/paleo/pdsiyear.html>. It is the first of its kind, providing a history of drought on this continent. The atlas contains annual maps of reconstructed droughts over North America, including an animation of those maps showing aridity over time.

Observed Thinning of West Antarctic Glaciers.[22,23] In the wake of the Larsen B Ice Shelf disintegration in 2002 (see Figure 5), glaciers in the Antarctic Peninsula have thinned and their movement to the Weddell Sea has accelerated. According to another study conducted by U.S. and Chilean researchers, glaciers in West Antarctica are shrinking at a rate substantially greater than was observed in the 1990s. They are losing 60% more ice into the Amundsen Sea than they accumulate from inland snowfall. The ice loss from the measured glaciers corresponds to an annual sea-level rise of 0.2 mm (0.008 in), or more than 10% of the total global increase of about 1.8 mm (0.07 in) per year. Ice shelves in the Amundsen Sea appear to be thinning, offering less resistance to their tributary glaciers. The findings suggest that ice shelf breakup may lead to an increased rate of sea-level rise.

Projected Heat Wave Intensity, Frequency, and Duration.[16] Results under a "business-as-usual" scenario using a global coupled climate model (the Parallel Climate Model, PCM) project a geographic pattern to future changes in heat waves. This model projects that areas in Europe and North America could experience more intense, more frequent, and longer lasting heat waves in the second half of the 21st century. Observations show that present-day heat waves over Europe and North

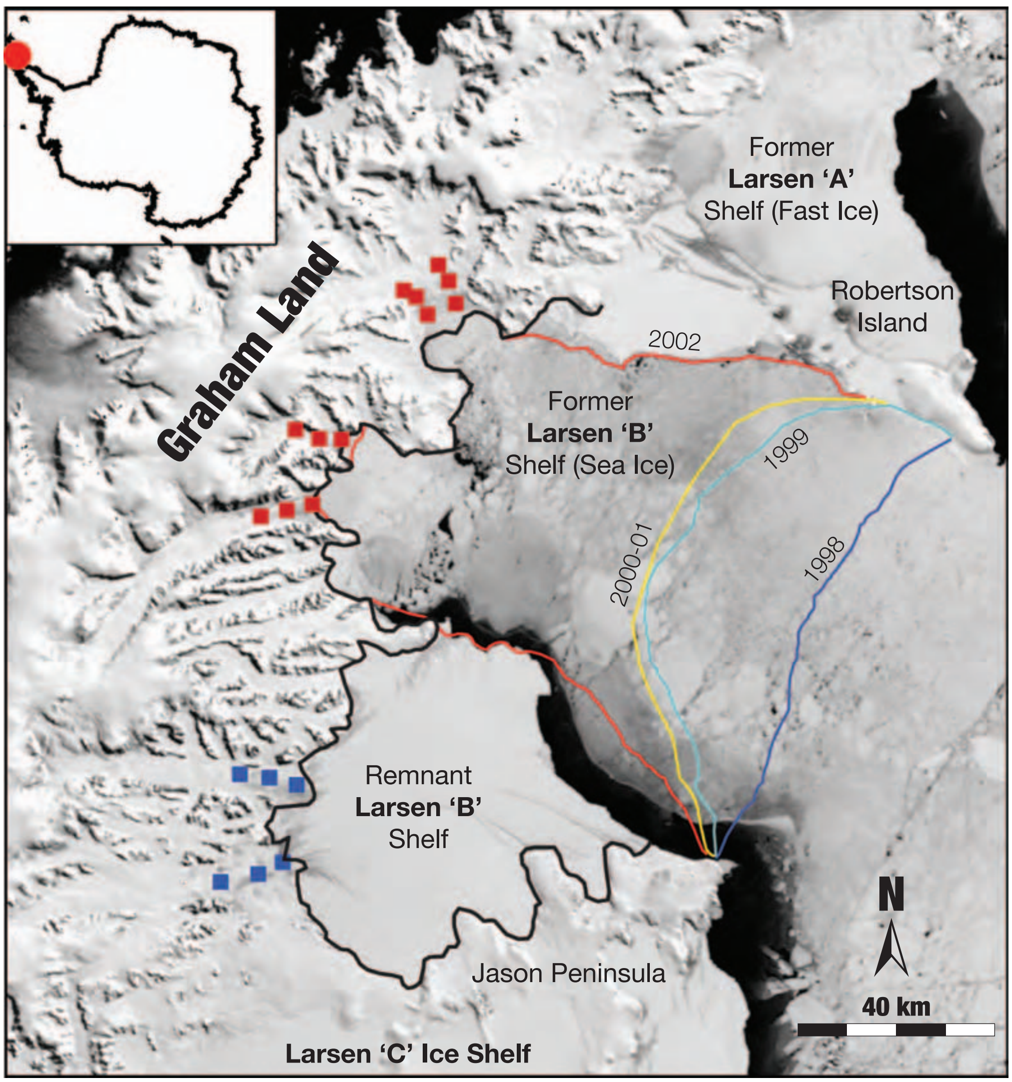


Figure 5: Retreating Margin of the Larsen B Ice Shelf. Colored lines show the retreating margin of the Larsen B ice shelf from 1998 through 2002. The red squares indicate glacier velocity measurement sites where speed increased significantly in the 12 months following the 2002 ice shelf breakup—up to a five-fold flux increase in some places. Measurements at sites indicated by the blue squares showed no large velocity changes. The 1 November 2003 base image is from MODIS Terra. *Credit: T. Scambos, NOAA/ National Snow and Ice Data Center.*

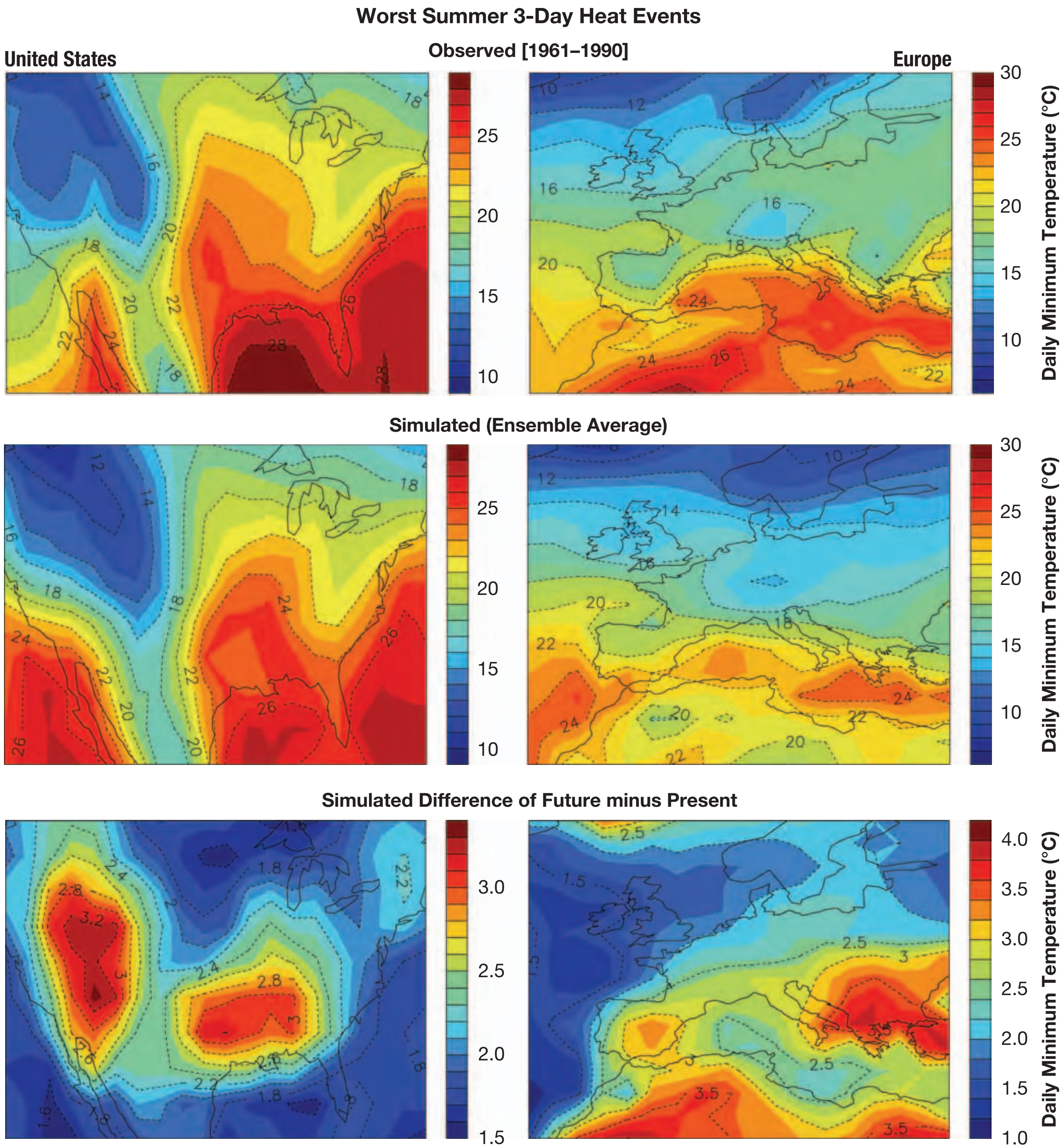


Figure 6: Worst Summer 3-Day Heat Events. The top row shows observed daily minimum temperature maps of the mean annual warmest 3-day heat waves in the United States (left) and Europe (right) for 1961 to 1990. The middle row shows the ability of the Parallel Climate Model to simulate these heat waves. The bottom row shows the increased heat wave intensities that are projected by the model for the United States and Europe in the period 2080 to 2099.
Credit: G.A. Meehl and C. Tebaldi, National Center for Atmospheric Research.

America coincide with specific atmospheric circulation patterns that are projected by the PCM to be intensified by increases in greenhouse gases (see Figure 6).

Projected Changes in Hurricane Intensity and Rainfall.[13] A recent study makes use of nine independent computer simulations of global climate change produced by different research institutions from around the world. In all, 1,300 simulated "hurricanes" were generated using a higher resolution version of a current operational hurricane model forced by 80-year future "business-as-usual" climate model projections. Results of this study indicate a modeled link between surface oceanic warming and a change in the intensity of simulated tropical storms. By 2080, the model-projected changes resulting from approximately doubled carbon dioxide concentrations could cause an average increase of approximately one-half a category in intensity (see Figure 7) and an 18% increase in rainfall within 60 miles of the storm's center. Better understanding is needed of how natural climate variations influence the frequency, severity, and favored paths of hurricanes, how the climate system responds to increased greenhouse gas concentrations, and how key physical processes (e.g.,

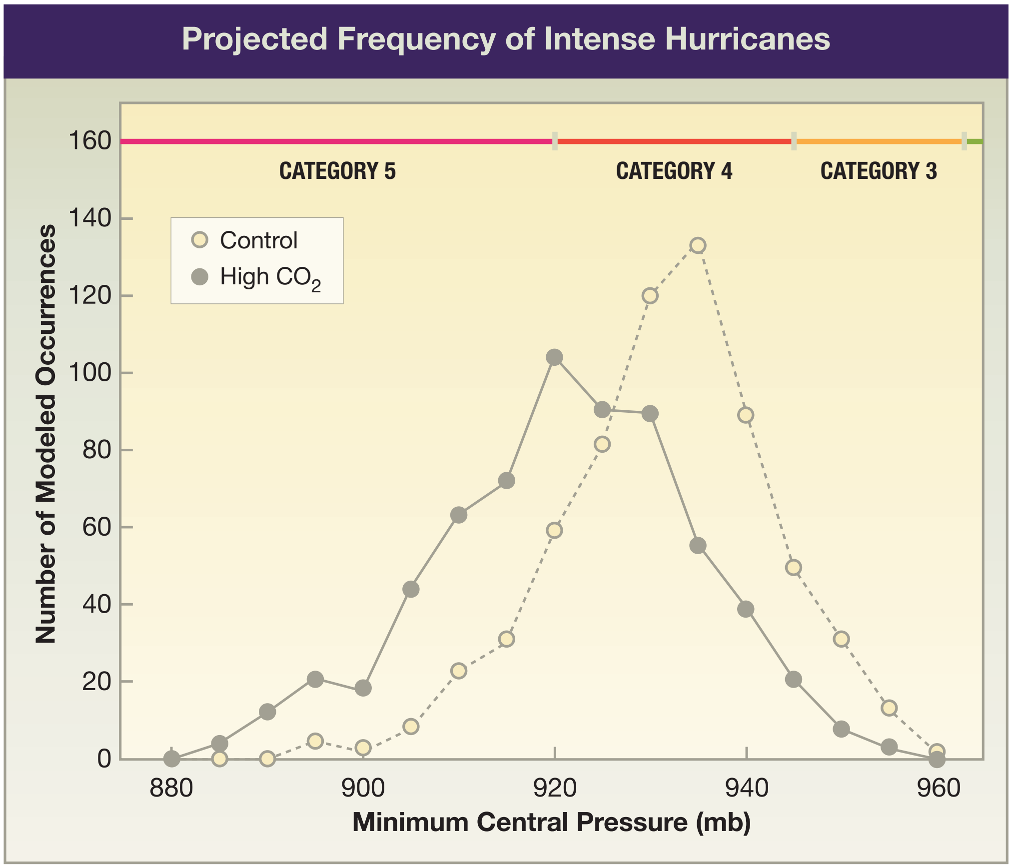
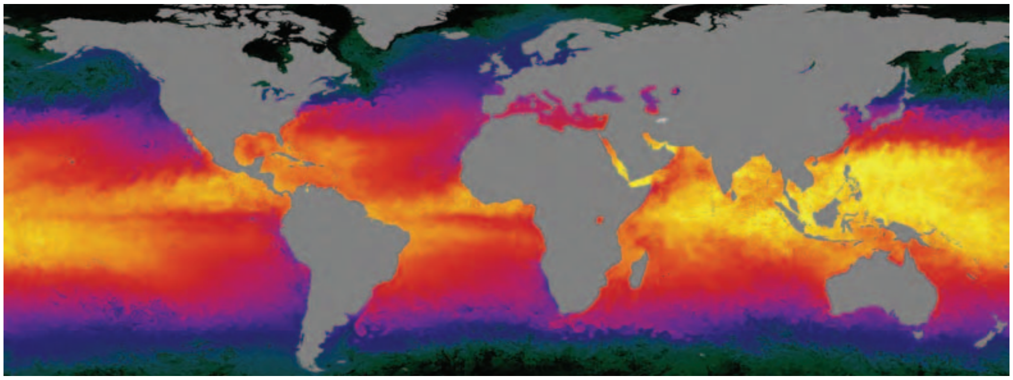


Figure 7: Projected Frequency of Intense Hurricanes. Via a high-resolution version of the GFDL hurricane prediction system, the model-projected increase in frequency of intense hurricanes can be seen by comparing the "control" simulation of a climate model run with present-day levels of greenhouse gases (yellow circles) to a simulation corresponding approximately to the year 2080 in which carbon dioxide levels were increased by 1% per year (brown circles). Category 4 hurricane wind speeds range from 131 to 155 mph and Category 5 wind speeds exceed 155 mph.
Credit: T. Knutson, NOAA/ Geophysical Fluid Dynamics Laboratory.

convection) are best represented in climate and hurricane models. It is essential that these advances be accompanied by improved understanding of the factors affecting societal vulnerability to hurricanes, including levels of coastal development, preparedness, and response systems.

Soot from Fossil Fuels Changes Snow Reflectivity.[10] Soot produced as a by-product of fossil-fuel burning can be carried for hundreds of miles before being deposited on the ground. Soot that falls on snow increases the snow's absorption of solar energy, thereby increasing its melting rate. Exposing bare ground may lead to further warming since it generally absorbs more solar energy than snow. A new study indicates that this effect may have contributed to some of the global warming of the past century, including a portion of the trend toward early springs in the Northern Hemisphere, thinning Arctic sea ice, and melting land ice.

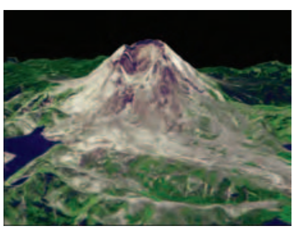
Subpolar North Atlantic Circulation Changes during the 1990s.[8] The giant vortex of an ocean current, or gyre, in the northwestern North Atlantic appears to have slowed. Observations of sea-surface height reveal that significant changes have occurred over the past decade in the mid- to high-latitude North Atlantic Ocean. TOPEX/Poseidon altimeter data show that the average sea-surface height increased during the 1990s in this region. The same measurements were used to infer that ocean surface current velocities likely declined during the 1990s in the subpolar gyre. Combining the data from earlier satellites, researchers found that this circulation pattern may have been weakening since at least the late 1970s. Direct observations in the boundary current of the Labrador Sea support this interpretation. The direct observations also indicate that the associated deep underwater current is weakening as well. These changes are potentially significant because the Atlantic Ocean circulation patterns are responsible for redistributing a substantial portion of Earth's heat from low latitudes to high latitudes, making Europe much warmer than it would be without these currents.



New Insights into Predictability of El Niño Events.[3] Forecasts of El Niño climate events are routinely provided and distributed, but the limits of how accurately and how far in advance El Niños can be predicted are still a subject of debate. Previous studies suggest that forecast abilities are largely limited by the effects of high-frequency atmospheric variations, or by the growth of small initial errors in model simulations. In a recent study using an advanced coupled ocean-atmosphere model, researchers made retrospective forecasts of the interannual climate fluctuations in the tropical Pacific Ocean for the period 1857 to 2003. This is several times longer than any previous experiment of this kind. The model demonstrated significant skill in predicting El Niño events back to the 19th century. Furthermore, strong El Niño events had some predictability up to 2 years in advance. The research suggested that El Niño events may be more predictable than previously thought. Additionally, the study suggests that one of the keys to better El Niño predictions is accurate initial conditions (i.e., the state of the ocean-atmosphere system as determined by observations of ocean temperatures, sea surface temperature, surface winds, etc., at the beginning of the model simulation).

Tropical Sea Surface Temperatures Affect Northern Hemisphere Winter.[11] Recent research suggests that long-term variability in tropical sea surface temperature (SST) has had an important effect on regional changes in the winter climate of the Northern Hemisphere during the last half of the 20th century. The warming of tropical Indian and western Pacific Ocean surface temperatures since 1950 has been related to unusual changes in the winter North Atlantic and European climate. The changes are characterized by a trend in indices of the North Atlantic Oscillation, the most recurrent regional pattern of atmospheric variability in the Northern Hemisphere mid-latitudes. The changes also include decadal-scale climate variability over the North Pacific Ocean and adjacent continents that affects agricultural harvests, water management, energy supply and demand, and fisheries yields. The link between northern climate variability and the tropical oceans suggests a potential basis for improving climate predictions. This work also indicates the potential value of determining the future course of tropical SST patterns for improving projections of regional climate changes.

Feasibility of Constructing Three-Dimensional Climate Analyses Prior to 1948.[25] A recent study has shown, for the first time, that it is possible to produce a three-dimensional depiction of the atmosphere back through at least the beginning of the 20th century. A number of such three-dimensional "reanalysis" data sets have been produced by integrating past observations together within state-of-the art climate models – but never before 1948, which is when upper-air observations made by weather balloons became broadly available. Extending the three-dimensional reanalyses to earlier time periods would significantly increase their potential to support a variety of applications that to date have not been possible for the first half of the 20th century, including improving descriptions and understanding of long-term variability in mid-latitude storm systems; improving understanding of the atmospheric circulation associated with extreme events such the 1930s drought in central North America or the prolonged wet period that led to overestimates of precipitation, hence over-allocation of water resources, in the Colorado River; and creating a longer period over which to evaluate climate models driven by changes in greenhouse gases, aerosols, and solar activity. The results suggest that reanalysis is feasible extending back as far as the late 19th century and may yield useful analyses from the surface through much of the lower troposphere at daily time resolution.



Developments in Climate Modeling[†]

A new generation of climate models has significantly improved representations of physical processes, as well as increased resolution, putting them at the forefront of international research. New simulations of climate change during the 20th century have been completed using these models. Various high-end modeling centers sponsored by DOE, NASA, NOAA, and NSF developed and tested the new models. All show significant improvements compared to their predecessors a decade ago.

Figure 8 shows an example of output from recent simulations using four of the leading U.S. climate models, compared with satellite-based observations. Although the detailed evolution of temperature differs in models and observations, both show a common picture of gradual stratospheric cooling, which is caused by the combined effects of ozone depletion and increases in well-mixed greenhouse gases. Superimposed

† Refer to the Climate Variability and Change Chapter References box on pages 52 and 53 for citations associated with the models discussed in this subsection, specifically reference numbers 2, 4, 5, 7, 9, 12, 14, 15, 17, 20, 21, 24, and 26.

on this overall cooling are the short-term (1- to 2-year) warming signatures of the El Chichón and Pinatubo volcanic eruptions.

U.S. climate modeling capability has advanced significantly in the last 4 years. Output from the four U.S. models shown in Figure 8 is available for the CCSP synthesis and assessment products and the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report*. An extensive database, including the output from these models, is archived and made accessible to interested climate researchers through an enabling technology (Earth System Grid; see <www.earthsystemgrid.org>) and the Program for Climate Model Diagnosis and Intercomparison (PCMDI; see <www-pcmdi.llnl.gov>). It is anticipated that upcoming analyses of these climate model projections will yield fresh insights into climate variability and change. A special interagency grants program was implemented to accelerate analyses of the 20th century historical simulations. A subset of the data useful for research on the potential effects of climate change on climate-sensitive resources and systems is being made available through the IPCC Data Distribution Center (DDC; see <ipcc-ddc.cru.uea.ac.uk/>). A major effort in

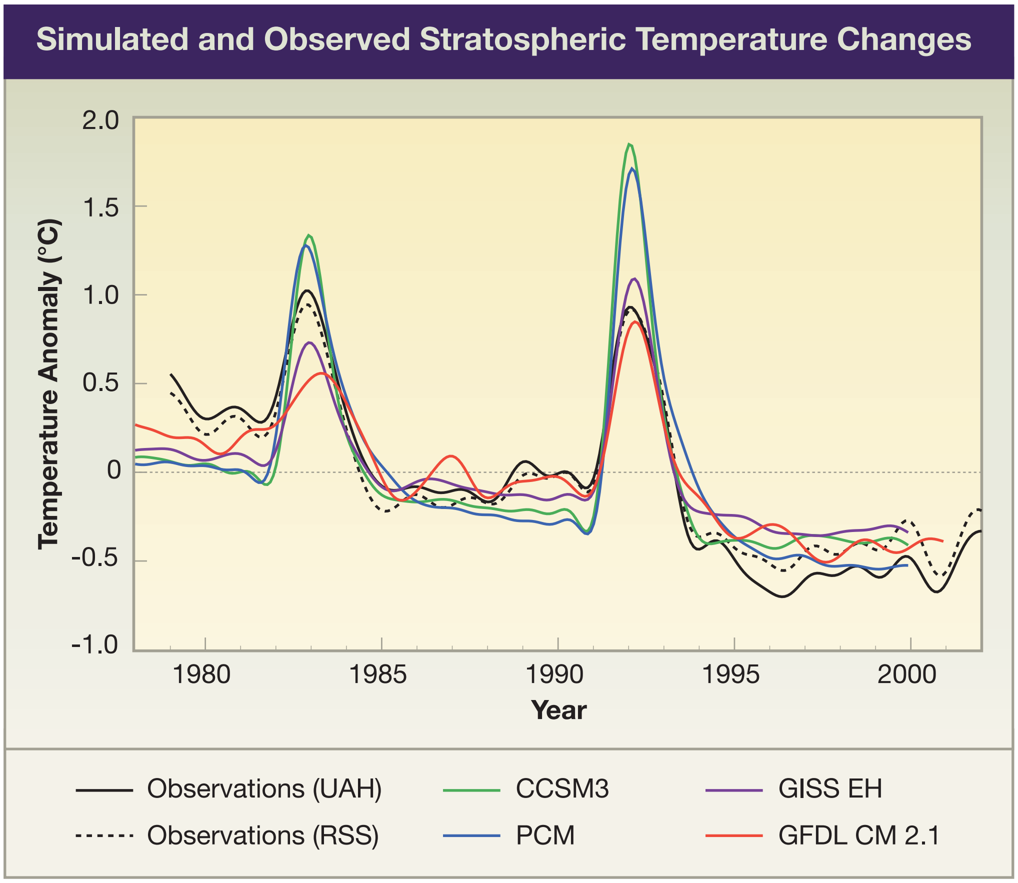
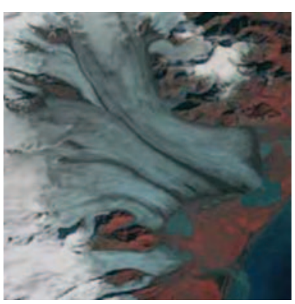


Figure 8: Simulated and Observed Stratospheric Temperature Changes. Globally averaged temperature anomalies for the lower stratosphere simulated by four global climate models using estimates of natural and anthropogenic forcings (in color) and observational values (in black) from two different satellite data sets. Model runs were conducted by the Parallel Climate Model (PCM, blue); the Community Climate System Model, version 3 (CCSM3, green); the Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM 2.1, red); and the Goddard Institute for Space Studies climate model (GISS EH, purple). Observed estimates of lower stratospheric temperature changes are from channel 4 of the satellite-based Microwave Sounding Unit—produced by the University of Alabama in Huntsville (UAH, solid black) and Remote Sensing Systems in Santa Rosa (RSS, dashed black).
Source: B. Santer, Lawrence Livermore National Laboratory.

the coming years will be to assess the capabilities of these and related models for simulating regional climate change. Preliminary indications are that these models possess some skill at regional scales.

Despite the recent model improvements, there are still significant uncertainties associated with aspects of climate models. One of these is the representation of clouds, which remains one of the weakest links in modeling the physical climate system. New integrated approaches have been developed to address this challenge, taking advantage of new high-resolution satellite data, field observations, and small-scale cloud models. Important work in this area is being carried out by the Climate Variability and Predictability (CLIVAR) program's Climate Process Teams supported by CCSP. The Climate Change Prediction Program–Atmospheric Radiation Program Parameterization Testbed (CAPT; see <www-pcmdi.llnl.gov/projects/model_testbed.php>) project is also addressing the cloud modeling problem through a novel approach that includes analyzing the ability of a climate model to accurately simulate weather events, diagnose the errors, and subsequently improve the model. One example of success in this work is an improved model representation of the processes that trigger precipitation. An improved model representation of vertical cloud overlap has been incorporated in the Geophysical Fluid Dynamics Laboratory (GFDL) and Canadian general circulation models as well as the European Centre for Medium-Range Weather Forecasts numerical weather forecast model.

As noted elsewhere in this report, improvements are being made in understanding and modeling other components of the Earth system, including atmospheric chemistry, ecosystems, and carbon cycling. Efforts are underway to integrate these efforts in increasingly comprehensive Earth system models.



Highlights of Plans for FY 2006

CCSP will continue to enhance observational and modeling capabilities for improved understanding, prediction, and assessment of climate variability and change. It will do so by vigorously pursuing the goals described in the *CCSP Strategic Plan*. The CVC activities planned for FY 2006 place particular emphasis on analyzing climate feedbacks and sensitivity to natural and human-induced forcing, as well as on improving climate modeling systems. The CVC efforts will continue to place high priority on research areas that can provide an improved scientific basis for informing critical policy and resource management decisions (see, for example, the box on CCSP synthesis and assessment products focused on the physical climate system). Some of the activities that will address these goals and emphases are described in the following subsections.

CCSP SYNTHESIS AND ASSESSMENT PRODUCTS

The *CCSP Strategic Plan* identifies 21 planned synthesis and assessment products describing the current state of knowledge concerning many different aspects of climate and global change. Examples of three of these, focused on the physical climate system, are outlined below.

Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. Independently produced data sets that describe the four-dimensional atmospheric temperature structure from the surface through the lower stratosphere indicate different temperature trends. These differences are seen in comparisons of separate *in situ* (surface and weather balloon) data sets, in comparisons of separate space-based data sets, and in comparisons of individual data sets drawn from the different observational platforms and different trend analysis teams. While previous efforts have addressed these uncertainties, the complexities of the issue, coupled with shortcomings of the available observing systems, have left a number of fundamental questions unanswered. Recent work with weather balloon and satellite data sets has provided new material for analysis and interpretation that will be included in this synthesis and assessment product, which will describe the trends and uncertainties in the lower atmospheric temperature records. The report will also present recent modeling results to assess relationships between imposed forcings (natural and human-induced) and simulated effects. The report has been reviewed by the National Research Council (NRC) and will be disseminated in FY 2006.

Past Climate Variability and Change in the Arctic and at High Latitudes. The Arctic is characterized by significant natural variability but recently has warmed more rapidly than almost any other region of the globe. The recent warming has been accompanied by a decrease in sea-ice cover and thickness and a decrease in ocean salinity. In addition, the permafrost has melted significantly in recent years. The impacts on humans and ecosystems associated with these changes were recently reported in the *Arctic Climate Impact Assessment*. This international study was partially funded by CCSP participating agencies. The Arctic and High Latitude Synthesis and Assessment Product will focus on the state of knowledge concerning past changes in the physical climate of this region, including how the recent changes compare to the longer term record and the extent to which they are historically unique. This information is vital since high-latitude regions are projected to experience the greatest warming in the future. The prospectus is currently being developed for this report. The bulk of the work on this product will be carried out in FY 2006.

Climate Models and Their Uses and Limitations, including Sensitivities, Feedbacks, and Uncertainty Analysis. Computer simulation models of the coupled atmosphere-land-ocean-sea ice system are essential scientific tools for understanding and predicting natural and human-caused changes in the Earth's climate. The purpose of this CCSP report is to provide guidance for the appropriate application of climate models and results of climate model experiments. It will describe the strengths and limitations of climate models at different spatial and temporal scales. It will focus on natural and human-caused factors influencing climate variability and change during the period 1870 to 2000, and will characterize sources of uncertainties in comprehensive coupled climate models, as well as high-resolution models used to downscale the coupled model results to regional scales. The prospectus is currently being developed for this report. The bulk of the work on this product will be carried out in FY 2006.

Key Climate Modeling Research Plans for FY 2006

Develop and Utilize Improved Climate Models. A number of modeling-related payoffs will occur in FY 2006, building on CCSP's broad range of CVC-related research activities. Several new climate model versions will be released and several new model simulations will be performed, providing an unprecedented perspective on past and future climate change:

- NASA's Goddard Institute for Space Studies (GISS) is scheduled to release a new climate model (Model E), containing a number of improved components. It will be more modular than previous versions, allowing its components to be tested in other models. NASA will also release a new version of the GEOS atmospheric climate model (GEOS5). This next-generation climate model will be coupled with the NOAA National Centers for Environmental Prediction (NCEP) system for assimilating meteorological observations into a standard framework. This will provide an important tool for the research community to assess the model's ability to simulate weather events. GEOS5 includes components developed jointly with the National Center for Atmospheric Research (NCAR), NCEP, and GFDL.

- Developmental and historical runs will be carried out at GFDL with an Earth system model that includes interactive chemistry, carbon, and nitrogen cycles. GFDL will produce climate simulations for research and assessment based on emission scenarios developed through the Climate Change Technology Program. Likely case studies will include exploring the range of plausible future environmental consequences of various emission rates resulting from combinations of different technologies.
- Development of the next-generation Community Climate System Model (CCSM-4) at NCAR will continue, and will include atmospheric chemistry, coupled biogeochemistry, and middle atmosphere components, as well as improved physics and dynamical components. In FY 2006, researchers involved in the CCSM activity will be undertaking research and model development in areas that are often not included in climate models – for example, stratosphere-troposphere interactions (including interactive atmospheric chemistry), biogeochemical feedbacks due to carbon, and other key components. In addition, a complete suite of CCSM and PCM ensemble simulations will be performed under various IPCC forcing scenarios.
- Ambitious new approaches are being developed that have the potential to leapfrog some of the limitations of existing climate modeling methodologies. One approach is the development of a geodesic climate model that uses a radically new grid for both the atmosphere and ocean, intended to solve many of the long-known problems with both latitude-longitude grids and spectral methods. The model also uses "floating" vertical coordinates for both the atmosphere and ocean. Another novel approach is a multi-scale modeling framework that embeds cloud-resolving models in climate models. This addresses one of the most confounding issues in simulating future climate: accurately representing cloud effects despite the coarse grids of current models.
- A Modeling, Analysis, and Prediction Modeling Environment will be implemented in FY 2006 to provide open access and collaboration among Government agencies and the research community developing Earth system models and components.

These activities will address Goals 1, 2, and 3 of the CCSP modeling strategy, Goal 2 of the CCSP decision support strategy, and Questions 3.5, 4.1.4, and 7.5 of the CCSP Strategic Plan.

Archive, Distribute, and Analyze Model Output. Multi-century climate simulations produced by high-end climate models, both nationally and internationally, will be archived and distributed by PCMDI. This program will continue to make these invaluable data sets available to the climate research community and other stakeholders through enabling technologies such as the Earth System Grid, which addresses the formidable challenges associated with analyzing the massive amounts of data produced by global Earth system models. Through a novel combination of computer technologies, the Earth System Grid will provide a seamless and powerful environment that facilitates these analyses intended to improve understanding of models' strengths, weaknesses, and opportunities for improvement. Comparisons between the observed and simulated global and regional climates of the late 19th and 20th centuries will be completed and published in FY 2006 under the Climate Model Evaluation Project. These diagnostic analyses are the latest in an ongoing series of model performance assessments that are providing a valuable yardstick for evaluating the quality of climate projections into the 21st and 22nd centuries.

These activities will address Goals 2 and 3 of the CCSP modeling strategy,
Goal 2 of the CCSP decision support strategy,
and Goals 1, 2, and 4 of the CCSP data management and information strategy.

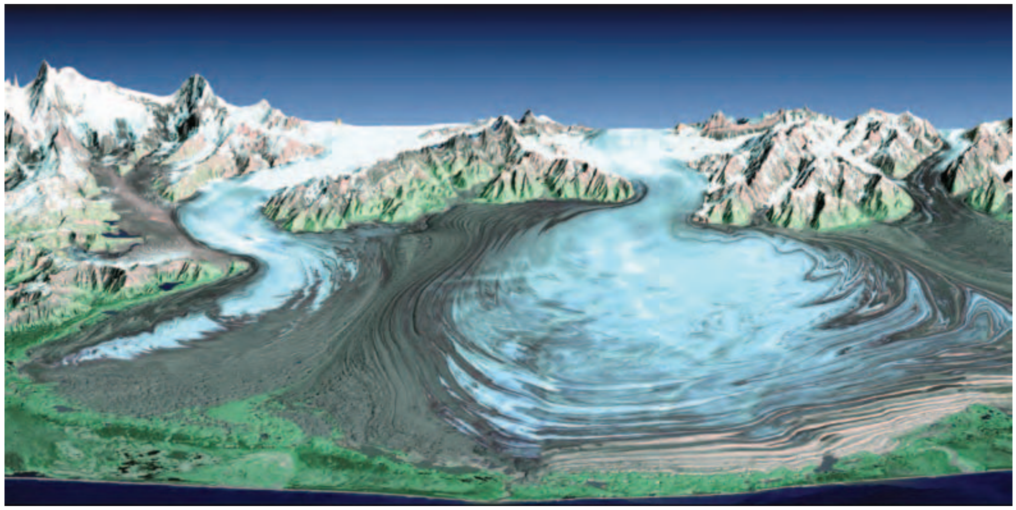
Key Observations and Process Studies Research Plans for FY 2006

Detection and Attribution of Climate Change. One of the most important questions in climate science is the extent to which humans have caused and may continue to cause climate change. Model results are sensitive to uncertainties in the "forcing factors" that lead to climate change over time. Refined estimates of forcing variables such as solar output and aerosol concentrations (both volcanic and human-induced) will be used as inputs for paleoclimate and modern model runs. The results will be evaluated in FY 2006 for the magnitude and pattern of climate response to these variables. This effort will provide the most rigorous assessment to date of the uncertainty in model-derived fingerprints of anthropogenically and naturally forced climate change. Inter-model differences will be explicitly accounted for in the detection methodologies to further understand sources of uncertainty in attribution claims.

These activities will address Goal 1 of the CCSP modeling strategy
and Question 4.1.5 of the CCSP Strategic Plan.

Improve Understanding of Abrupt Climate Change. The *CCSP Strategic Plan* identifies abrupt climate change as a high-priority research topic. Ongoing research will continue to focus on the mechanisms that may give rise to abrupt climate changes, their potential predictability, and regional to global impacts. A synthesis report of modern and paleoclimate observations and modeling results from work of the Consortium on the Oceans Role in Climate – Abrupt Climate Change Studies over the past 5 years will be produced, which may be used to help inform future abrupt climate change research approaches.

These activities will address Questions 4.3.1, 4.3.3, and 4.3.5 of the CCSP Strategic Plan.



Analyze Arctic Processes. Arctic processes are expected to be sensitive to climate change and are generally expected to play an important role in modulating climate change. The Mixed-phase Arctic Cloud Experiment (M-PACE) will analyze and report results of the field experiment conducted on the North Slope of Alaska in fall 2004 to improve the scientific understanding of the dynamic processes in Arctic clouds, including cloud microphysical processes and energy transfer through clouds. In addition, a prototype Arctic observing system is being created for monitoring sea ice, ocean heat content, freshwater fluxes, and ecosystem indicators.

This activity will address Goal 1 of the CCSP modeling strategy, Goal 1 of the CCSP observing and monitoring strategy, and Questions 4.1.1, 4.1.2, and 4.3.7 of the CCSP Strategic Plan.

Great Lakes Paleoclimatology. The paleoclimatology of the Great Lakes region between 9,400 and 7,700 calendar years before present will be studied in FY 2006. Three primary issues will be examined: correlation of Great Lakes low water stands to other paleoclimatic variables; evaluation of paleoclimate variability using multi-proxy data to determine past atmospheric conditions; and reconstruction of the region's paleogeography in order to model climatic and hydrologic conditions there. This study is part of a broader effort within CCSP to develop improved quantitative paleoclimatic estimates, particularly of variability on short time scales.

This activity will address Questions 4.2.6, 4.3.2, 4.4.1, 4.4.2, and 4.4.3 of the CCSP Strategic Plan.

Develop and Test New Model Parameterizations. Climate Process and Modeling Teams are identified in the *CCSP Strategic Plan* as an important avenue for improving model representations of key climate system processes. Climate Process and Modeling Teams are multi-agency teams of university, laboratory, and modeling center scientists. In FY 2006 they will test new model representations of clouds, the flow of water along the ocean bottom, and the mixing of water in the upper ocean by small-scale circulation features (eddies). The CAPT framework, mentioned previously, will also make significant contributions to model improvements in FY 2006 by employing a new testbed for evaluating important aspects of the GFDL AM2 atmospheric model.

These activities will address Goals 1, 2, and 3 of the CCSP modeling strategy and Questions 4.1.1, 4.1.2, 4.1.6, and 4.2.1 of the CCSP Strategic Plan.

Improve Understanding of Atlantic Climate System Processes. The United States will lead and participate in numerous studies of marine processes that must be better understood to improve predictions of climate variability. One region of particular focus for CCSP in FY 2006 is the Atlantic Ocean, where CCSP will play a prominent role in the CLIVAR Mode Water Dynamic Experiment (CLIMODE), the Tropical Atlantic Climate Experiment (TACE), and the African Monsoon Multidisciplinary Analyses (AMMA). CLIMODE will investigate how deep subtropical waters of the North Atlantic Ocean form in a region of strong air-sea heat exchange, south of the Gulf Stream. This project is a mix of modeling and *in situ* and satellite-based observations, which is expected to produce improved model representations of air-sea heat exchange. TACE will investigate a region of the Atlantic where many climate models poorly simulate sea surface temperature. Through a unique combination of observations and modeling efforts, TACE will attempt to improve understanding of the coupled atmosphere-ocean processes in this region and improve their representation in climate models. U.S. involvement in AMMA will focus on climate, weather, and related aerosol issues associated with African monsoon regions.

These activities will address Goal 1 of the CCSP modeling strategy and Questions 4.2.1, 4.2.4, and 4.2.5 of the CCSP Strategic Plan.

Analyze Warm Season Precipitation in the Southwestern United States. Research will continue on the processes that influence warm season precipitation over the southwestern United States and prospects and needs for improving summer rainfall forecasts in this region. The impacts of data obtained from the 2004 North American Monsoon Experiment on model analyses will be determined, and an assessment will be completed on the ability of global and regional models to simulate the 2004 North American summer monsoon.

This activity will address Questions 4.2.1 and 4.4.4 of the CCSP Strategic Plan.

CLIMATE VARIABILITY AND CHANGE CHAPTER REFERENCES

1) **Barron,** J.A., D. Burky, and W.E. Dean, 2005: Paleoceanographic history of the Guaymas Basin, Gulf of California, over the past 15,000 years. *Marine Micropaleonology*, **50(3-4)**, 185-207.
2) **Caya**, D. and S. Biner, 2004: Internal variability of RCM simulations over an annual cycle. *Climate Dynamics*, **22**, 33-46.
3) **Chen**, D., M.A. Cane, A. Kaplan, S.E. Zebiak, and D. Huang, 2004: Predictability of El Niño over the past 148 years. *Nature*, **428**, 733-736.
4) **Christy**, J.R., R.W. Spencer, W.B. Norris, and W.D. Braswell, 2003: Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *Journal of Atmospheric and Oceanic Technology*, **20**, 613-629.
5) **Collins**, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith, 2005: The Community Climate System Model: CCSM3. *Journal of Climate* (submitted).
6) **Cook**, E.R., C.W. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle, 2004: Long-term aridity changes in the western United States. *Science*, **306(5698)**, 1015-1018.
7) **Delworth**, T.L., A.J. Broccoli, A. Rosati, R.J. Stouffer, V. Balaji, J.A. Beesley, W.F. Cooke, K.W. Dixon, J. Dunne, K.A. Dunne, J.W. Durachta, K.L. Findell, P. Ginoux, A. Gnanadesikan, C.T. Gordon, S.M. Griffies, R. Gudgel, M.J. Harrison, I.M. Held, R.S. Hemler, L.W. Horowitz, S.A. Klein, T.R. Knutson, P.J. Kushner, A.R. Langenhorst, H.-C. Lee, S.-J. Lin, J. Lu, S.L. Malyshev, P.C.D. Milly, V. Ramaswamy, J. Russell, M. Daniel Schwarzkopf, E. Shevliakova, J.J. Sirutis, M.J. Spelman, W.F. Stern, M. Winton, A.T. Wittenberg, B. Wyman, F. Zeng, and R. Zhang, 2005: GFDL's CM2 global coupled climate models – Part 1: Formulation and simulation characteristics. *Journal of Climate* (accepted).
8) **Hakkinen**, S. and P. Rhines, 2004: Decline of subpolar North Atlantic circulation during the 1990s. *Science*, **304**, 555-559.
9) **Hansen**, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G. A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R. Miller, P. Minnis, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao, and S. Zhang, 2005: Efficacy of climate forcings. *Journal of Geophysical Research*, **110**, D18104. doi:10.1029/2005JD005776.
10) **Hansen**, J. and L. Nazarenko, 2004: Soot climate forcing via snow and ice albedos. *Proceedings of the National Academy of Sciences*, **101(2)**, 423-428.
11) **Hoerling**, M.P., J.W. Hurrell, T. Xu, G.T. Bates, A.S., Phillips, 2004: Twentieth century North Atlantic climate change. Part II: Understanding the effect of Indian Ocean warming. *Climate Dynamics*, **23**, 391-405.
12) **Klein**, S.A., R. Pincus, C. Hannay, K.-M. Xu, 2005: How might a statistical cloud scheme be coupled to a mass-flux convection scheme? *Journal of Geophysical Research*, **110**, D15S06.
13) **Knutson**, T.K. and R.E. Tuleya, 2004: Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *Journal of Climate*, **17(18)**, 3477-3495.
14) **Mears**, C.A., M.C. Schabel, and F.W. Wentz, 2003: A reanalysis of the MSU channel 2 tropospheric temperature record. *Journal of Climate*, **16**, 3650-3664.
15) **Meehl**, G.A., W.M. Washington, B.D. Santer, W.D. Collins, J.M. Arblaster, A. Hu, D.M. Lawrence, H. Teng, L.E. Buja, and W.G. Strand, 2005: Climate change in the 20th and 21st centuries and climate change commitment in the CCSM3. *Journal of Climate* (accepted).
16) **Meehl**, G.A. and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994-997.

CLIMATE VARIABILITY AND CHANGE CHAPTER REFERENCES (CONTINUED)

17) **Pincus**, R., C. Hannay, S.A. Klein, K.-M. Xu, R. Hemler, 2005: Overlap assumptions for assumed probability distribution function cloud schemes in large-scale models. *Journal of Geophysical Research*, **110**, D15S09.
18) **Pollack**, H.N. and J.E. Smerdon, 2004: Borehole climate reconstructions: Spatial structure and hemispheric averages. *Journal of Geophysical Research*, **109**, D11106. doi:10.1029/2003JD004163.
19) **Poore,** R.Z., M.J. Pavich, and H.D. Grissino-Mayer, 2005: Record of North American southwest monsoon from Gulf of Mexico sediment cores. *Geology*, **33(3)**, 209-212.
20) **Ramaswamy**, V., M.-L. Chanin, J. Angell, J. Barnett, D. Gaffen, M. Gelman, P. Keckhut, Y. Koshelkov, K. Labitzke, J.-J.R. Lin, A. O'Neill, J. Nash, W. Randel, R. Rood, K. Shine, M. Shiotani, and R. Swinbank, 2001: Stratospheric temperature trends: Observations and model simulations. *Reviews of Geophysics*, **39(1)**, 71-122.
21) **Roads**, J.O., 2004: Experimental weekly to seasonal, global to regional U.S. precipitation forecasts. *Journal of Hydrology*, **288**, 153-169.
22) **Scambos**, T.A., J.A. Bohlander, C.A. Shuman, and P. Skvarca, 2004: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters*, **31**, L18402. doi:10.1029/2004GL020670.
23) **Thomas**, R., E. Rignot, G. Casassa, P. Kanagaratnam, C. Acuna, T. Akins, H. Brecher, E. Frederick, P. Gogineni, W. Krabill, S. Manizade, H. Ramamoorthy, A. Rivera, R. Russell, J. Sonntag, R. Swift, J. Yungel, and J. Zwally, 2004: Accelerated sea-level rise from West Antarctica. *Science*, **306(5694)**, 255-258.
24) **Washington**, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner Jr., T.W. Bettge, A.P. Craig, W.G. Strand, J. Arblaster, V.B. Wayland, R. James and Y. Zhang, 2000: Parallel Climate Model (PCM) control and transient simulations. *Climate Dynamics*, **16**, 755-774.
25) **Whitaker**, J.S., G.P. Compo, X. Wei, and T.M. Hamill, 2004: Reanalysis without radiosondes using ensemble data assimilation. *Monthly Weather Review*, **132**, 1190-1200.
26) **Xie**, S., M. Zhang, J.S. Boyle, R.T. Cederwall, G.L. Potter, and W. Lin, 2004: Impact of a revised convective triggering mechanism on Community Atmosphere Model, Version 2, simulations: Results from short-range weather forecasts. *Journal of Geophysical Research*, **109**, D14102.