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.

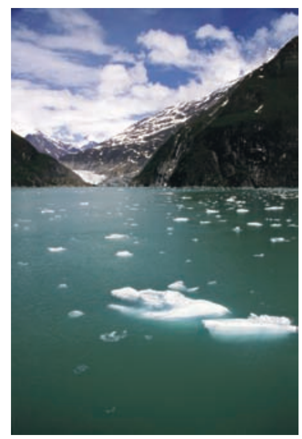
Climate variability and change occur across a broad range of time scales, from short-term variations that contribute to droughts, floods, and changes in hurricane activity, to longer term variations and changes that occur at decadal, centennial, and millennial time scales. CCSP-supported research has focused on advancing understanding of the causes of climate variations across this broad spectrum of time scales, and developing new capabilities to predict future climate variability and project longer term changes due to both natural and anthropogenic forcing. Increasingly, advances from CCSP-sponsored research are being used to develop new climate products and provide science-based information required by decisionmakers, policymakers, and stakeholders to deal with critical issues at local to national levels.

As defined in the *CCSP Strategic Plan*, the Climate Variability and Change (CVC) research component focuses on two broad, critically 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?

More specifically, CVC research addresses the five strategic research questions listed on the facing page in order to achieve the milestones, products, and payoffs described in the *CCSP Strategic Plan*. Cooperative efforts involving several CCSP agencies have led to significant progress in addressing all five of these strategic questions. The highlights below provide a cross-section of some of the major scientific advances achieved during this past fiscal year and illustrative examples of plans for FY 2007.

HIGHLIGHTS OF RECENT RESEARCH



The highlights of recent research on climate variability and change presented here are generally arranged by time scale, extending from paleoclimate through more recent climate characterizations. Additional subsections illustrate important progress in understanding fundamental climate processes and in identifying projected changes. The topics "Climate Model Evaluation, Diagnosis, and Improvement" and "Detection and Attribution of Climate Change" are given special attention in this section.

Paleoclimate

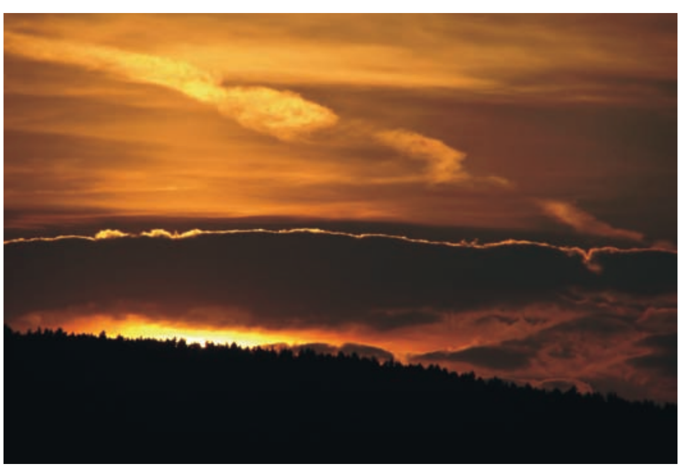
This section begins with an example of the use of paleoclimatic (i.e., prehistoric climate) data to improve understanding of natural climate variability.

High-Resolution Records of Prehistoric Climate.[4,10,30,37,42,44,56] Researchers have developed new high-resolution data records detailing paleoclimatic variations in ancient terrestrial and marine environments. Many of the records span the last ten to twenty thousand years, and some extend back several million years. These records, which are based on a variety of climate proxies (e.g., tree rings, pollen, fossil shells, foraminifera, diatoms), are being used to document multi-decadal and longer term trends in temperature and precipitation. This information is also being used to evaluate climate system variability, such as the influences of solar variability, changes in the position of the Intertropical Convergence Zone (ITCZ), and effects of large-scale climate patterns and processes (e.g., the North Atlantic Oscillation and El Niño) on regional climate. New data from rapidly accumulating sediments have also provided evidence of abrupt climate changes in the past related to changes in deep ocean circulation and other processes. Many of the records are the results of published scientific research contributed to the World Data Center for Paleoclimatology, operated by the National Climatic Data Center (<www.ncdc.noaa.gov>). For proxy information relevant to surface temperature reconstructions over the last 1,200 years or so, considerable effort has gone into testing the sensitivity of the reconstructions to the methods used. Recent results are in general agreement with previously published hemispheric-scale reconstructions and suggest that further improvements will depend more on the quality, rather than the quantity, of available proxy data. This conclusion and, more generally, the state of the science in reconstructing surface temperature records over the past one to two millennia, was the topic of a recent report by a panel of the National Research Council (NRC).

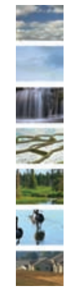
Recent Observed Changes

The following research highlights illustrate some recently observed climate system changes.

CCSP Synthesis and Assessment Report on Atmospheric Temperature Trends.[6,31,45,48] Taking advantage of new surface, satellite, and radiosonde data and new model simulations of 20th century climate, CCSP Synthesis and Assessment Product 1.1 addresses temperature changes from the surface through the lower stratosphere, differences in these changes at various levels, and our understanding of the causes of these changes and differences. It assesses progress made since production of reports by the NRC and the Intergovernmental Panel on Climate Change (IPCC) in 2000 and 2001, and highlights several fundamental uncertainties and differences between and within the individual components of the existing observational and modeling systems. It is particularly relevant to the CCSP Goal 1 focus on increasing confidence in the understanding of how and why climate has changed. The study focuses on the period since 1958, when upper-air soundings by balloon-borne instruments started to become widespread, and on the period since 1979, when the satellite era of atmospheric temperature sounding began. Conclusions include the following:



- *Surface Temperatures* – For global-mean changes, as well as in the tropics (20°S to 20°N), all data sets



show warming at the surface since 1958, with a greater rate of increase since 1979. The global average surface warming from 1958 to the present was 0.12°C per decade and the warming from 1979 to the present was 0.16°C per decade. Differences between various surface data sets are small.

- *Tropospheric Temperatures* – Global-mean temperature in the troposphere (the lower 10 km of the atmosphere) increased at about 0.14°C per decade since 1958, and between 0.10°C and 0.20°C per decade since 1979. In the tropics, temperature increased at about 0.13°C per decade since 1958, and between 0.02°C and 0.19°C per decade since 1979. All data sets show that the global-mean and tropical troposphere has warmed from 1958 to the present, with the warming in the troposphere being slightly more than at the surface. However, due to considerable disagreements between tropospheric data sets since 1979, it is not clear whether the troposphere has warmed more or less than the surface in the past two and half decades. Evidence suggests that non-climatic influences remaining in some or all of the observed tropical tropospheric data sets lead to biased long-term trends and are responsible for the large range in the observed values.
- *Lower Stratospheric Temperatures*: All data sets show that the stratosphere has cooled considerably from both 1958 and 1979 to the present, although there are large differences in the linear trend values from different data sets. Stratospheric cooling is expected from an increase in greenhouse gases. The largest differences between data sets are in the stratosphere, particularly between the radiosonde and satellite-based data sets. It is very likely that the satellite-radiosonde discrepancy arises primarily from uncorrected errors in the radiosonde data.

When state-of-the-art climate models are run with natural and human-induced forcings, simulated global-mean temperature trends for individual atmospheric layers are consistent with observations. Comparing trend differences between the surface and the troposphere exposes discrepancies between model simulations and observed data in the tropics. In the tropics, the majority of observational data sets show more warming at the surface than in the troposphere, while almost all model simulations have larger warming aloft than at the surface.

Several research efforts were catalyzed in part by the production of this synthesis and assessment product during the research community's input to its early stages. One of these studies concluded that an error in the satellite data associated with the day-night temperature cycle reduces the observed warming aloft. Another study concluded that changes in instrumentation of balloon-borne sensors have introduced a spurious cooling anomaly in upper air temperatures measured by those sensors. When these observational factors are accounted for, the observations and models come into closer agreement.

Melting Sea Ice.[9,38,53,59] On September 21, 2005, NASA and the National Snow and Ice Data Center observed the lowest extent of Arctic sea ice (5.3 million km^2) in the satellite record, which extends back to 1978 (see Figure 5). This brings the estimated decline in perennial Arctic sea ice to 9.8% per decade over the satellite record. The period 2002-2005 showed ice extents that were approximately 20% below the 1978-2000 average—a reduction in area of 1.3 million km^2 (or twice the size of Texas). The persistence of near-record low sea-ice extent raises concern that Arctic sea ice may be in a continual, long-term decline. Models driven by projected increases in greenhouse gases project a decrease in summer sea ice of more than 50% over the 21st century, although such projections should be tempered by the recognition that simulations of present-day sea ice generally differ from observed seasonal and geographical distributions. According to paleoclimatic records, there is no evidence of an ice-free summer Arctic during the last 800 millennia.

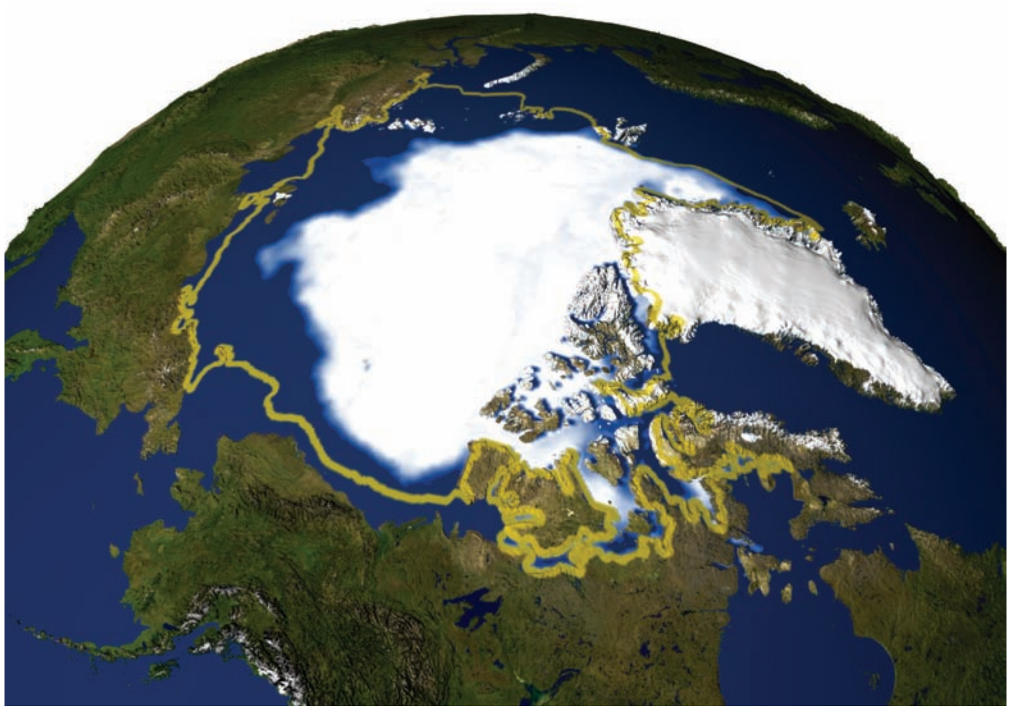


Figure 5: Arctic Minimum Sea-Ice Extent. MODIS color composite image of the Arctic showing the minimum sea-ice extent in 2005 (white) and the average of the 1979–2004 annual minima (yellow line). *Credit: G. Shirah, NASA/ Goddard Space Flight Center.*

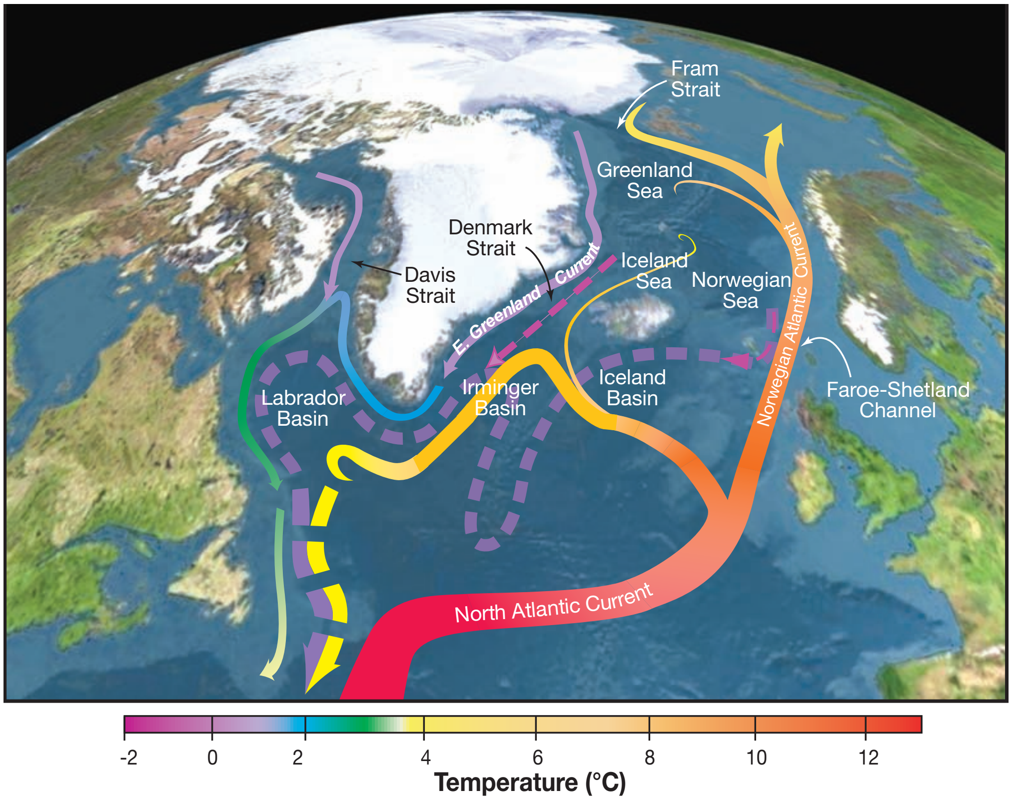
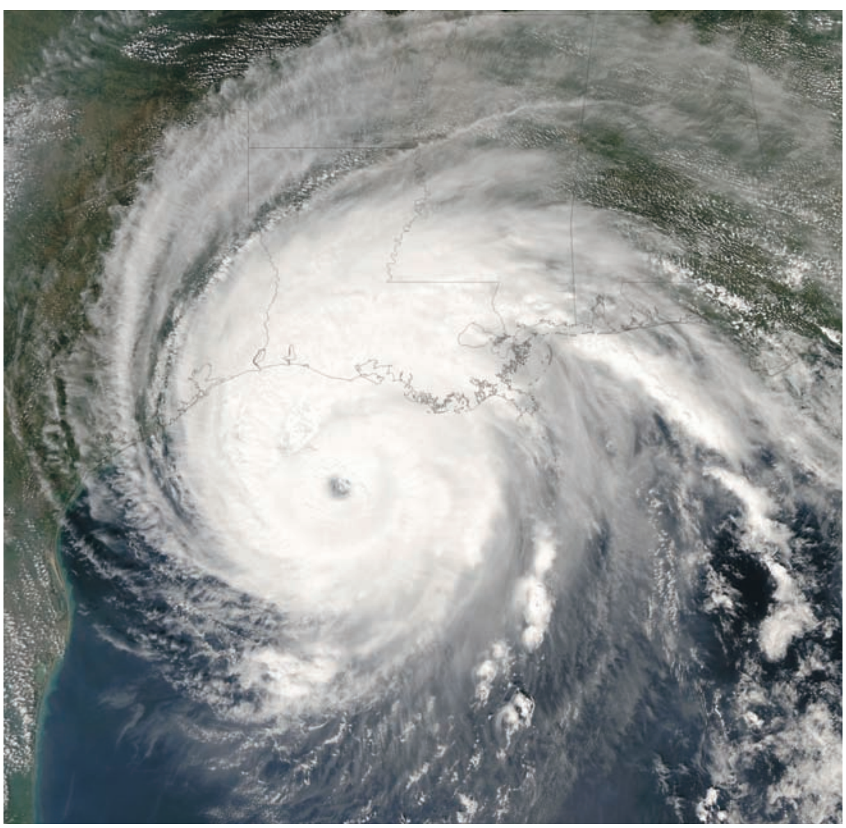


Figure 6: The Atlantic Meridional Overturning Circulation. Topographic map of the Nordic Seas and subpolar basins with schematic circulation of surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic meridional overturning circulation. Colors of curves indicate approximate temperatures. *Credit: R. Curry, Woods Hole Oceanographic Institution (reproduced with permission from* **Science***).*

Declining North Atlantic Salinity.[11] An analysis of oceanographic salinity data indicates that large amounts of freshwater have been added to the northern North Atlantic Ocean since the mid-1960s. This work quantified for the first time the volume and time evolution of this freshwater intrusion as well as its extension into the Nordic Seas and subpolar basins. The pattern of freshwater accumulation observed in the Nordic Seas suggests it would take nearly a century to reach freshening thresholds that could abruptly shut down the primary processes governing the meridional overturning (thermohaline) circulation in the North Atlantic. This circulation pattern, which consists of a northward surface component and a southward deep ocean component, is particularly important because it helps maintain relatively moderate temperatures in western Europe, among other things (see schematic diagram in Figure 6).

Fewer Days of Ice on Northern New England Rivers.[20] The total number of days of ice on northern New England rivers has declined significantly in recent decades, particularly in the spring. In a recent study, hydrologists examined data from streamflow gauging stations in Maine, New Hampshire, and Vermont that measure the height and flow of rivers. They examined the number of days each year of ice-affected flow—that is, days when there is enough ice in a river to affect the relation between the height and the flow of the river. They found that the number of ice-affected flow days decreased significantly during the 20th century for 12 of the 16 rivers studied. The total days of ice-affected flow decreased by an average of 20 from 1936 to 2000, with most of the decrease occurring since the 1960s. On average, ice-out dates were 11 days earlier in 2000 compared to 1936, again with most of the change occurring since the 1960s. The changes are consistent with warming temperatures in the late winter and spring in New England during the last 30 to 40 years. Another study of lakes in the region showed that ice-out dates were approximately 5 days earlier in 2000 compared to 1968 in northern and mountainous areas of Maine and New Hampshire and approximately 13 days earlier in more southerly areas of these states.

Hurricane Intensity Trends.[13,14,23,40,41,54] A pair of studies suggests a global average increase in the overall intensity, but not frequency, of hurricanes over approximately the last three decades. One study found a trend toward increasing potential destructiveness of tropical storms, as measured by "total power dissipation" measured over the lifetime of the storms. Changes in potential destructiveness were highly correlated with long-term trends in tropical sea surface temperatures (SSTs) over this period. A second study found a large increase in the number and proportion of hurricanes reaching very intense status, as defined by Saffir-Simpson categories 4 and 5, with the greatest increases occurring in the North Pacific, Indian, and southwest Pacific Oceans. As in the first study, the intensity increases are correlated with long-term increases in tropical SSTs observed in the global oceans. Interestingly, the overall numbers of tropical cyclone days have decreased in all of the global ocean basins except the North Atlantic over the past few decades. While these studies are consistent, the results do not definitively link the trends in tropical cyclone intensity to global warming, and some experts caution that deficiencies in past observations of hurricanes preclude confident identification of trends over this period. Other work has emphasized the vital importance of changing demographics and land use in coastal regions in increasing societal vulnerability to these storms, independent of any changes in hurricane intensity or frequency.



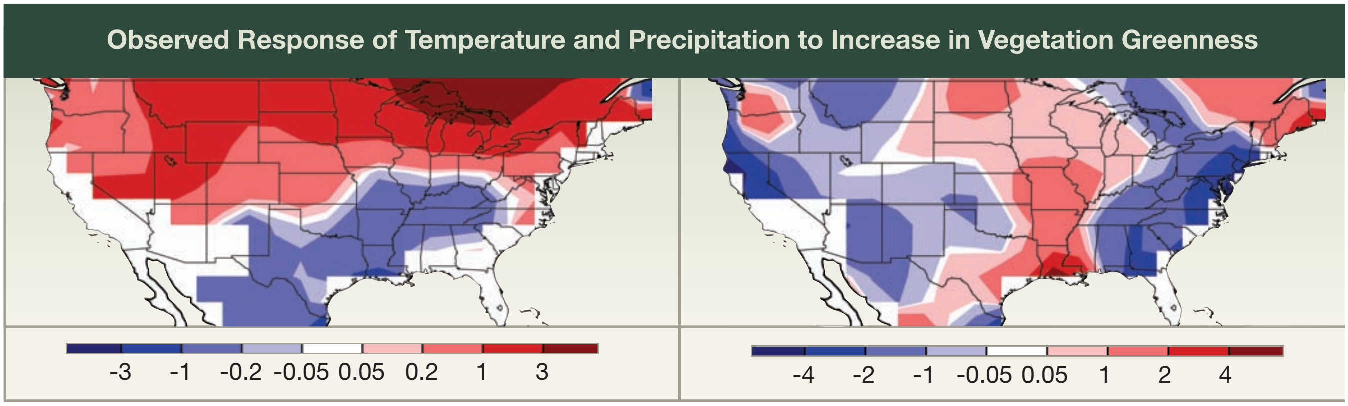


Figure 7: Observed Response of Temperature and Precipitation to Increase in Vegetation Greenness. (Left) Observed response of temperature to an increase in vegetation greenness, calculated from satellite observations. The units are °C per 0.1 FPAR (fraction of photosynthetically available radiation absorbed by the plant canopy). This illustrates vegetation feedbacks on temperature resulting from month-to-month variability in leaf and plant amount. (Right) Same as the left figure, but showing the response of precipitation to a change in vegetation. Units are cm/month per 0.1 FPAR. *Credit: Z. Liu, University of Wisconsin (reproduced from the* ***Journal of Climate*** *with permission from the American Meteorological Society).*

Fundamental Understanding of Climate Processes

Much of the work within the CVC research element focuses on improving fundamental understanding of climate processes. The following research highlights are examples of this type of work.

Vegetation-Climate Feedback.[28,35] While it is well known that climate is an important driver of vegetation growth, less is known about the potential influence of vegetation on climate. To date, two-way vegetation-climate interactions (i.e., feedbacks) have been mostly studied using computer models with minimal attempt to investigate observed feedbacks. Recent studies have made initial attempts to quantify the impacts of vegetation variability on climate using observed data. One of these studies assessed observed vegetation feedbacks on surface air temperature and precipitation across the United States using satellite-derived vegetation data and observed monthly climate data for 1982-2000. The results show that an increase in vegetation generally leads to a substantial increase in temperature across the northern states, particularly in the spring. The impact of vegetation on precipitation appears to be more complex and relatively weak. It appears that an increase in vegetation over the major croplands of the United States supports an increase in precipitation. Figure 7 illustrates these responses.

Understanding and Modeling Ocean Mixing Processes.[7,15,25,46] Ocean mixing processes that are too small to be explicitly included in current climate models are an important area of research, since these processes largely determine the rate of heat uptake by the ocean. Two U.S. Climate Variability and Predictability (CLIVAR) Climate Process and Modeling Teams (CPTs), supported by NSF, NOAA, and NASA, have focused on improving the understanding and representation of ocean mixing processes in climate models. One CPT is working on how to include in climate models the ocean mixing that results when dense waters flow over steep ocean bottom features, mixing with overlying waters. One region where this occurs is in the North Atlantic (see the research highlight above on "Declining North Atlantic Salinity") where waters from the Arctic region sink and pass south into the Atlantic and help form the meridional overturning circulation. Comparisons of modeling approaches have been completed and evaluations of new treatments of these processes in the models are underway. The second ocean CPT is studying the transfer and mixing of ocean properties by small upper ocean features. These small eddies transport large amounts of heat in the Southern Ocean and in the Gulf Stream and Kuroshio Current regions and modulate the exchange of heat between the ocean and atmosphere in these regions. A recent study shows that "salt fingers," or filaments of salty water that sink in the ocean, play a more important role in vertical mixing of ocean waters than previously thought.

Projected Changes

The following highlights illustrate recent studies that have projected potential changes in future climate conditions based on simulations by state-of-the-art computer models.

Rainfall Extremes.[18,55] A set of recent modeling studies using the archived results of the IPCC Fourth Assessment Report models indicates that what would be considered a rare weather event at present may become commonplace by the end of this century. Furthermore, these rare events may increase in severity far more than changes in annual average conditions. For example, one study indicates that rainfall on the wettest day of the year is likely to increase more than changes in the average annual rainfall under conditions of increased greenhouse gases. Changes in such rainfall extremes may have larger impacts on the environment and society than changes in average annual rainfall. The results also suggest that the signature of greenhouse gas increases may be identified more easily from changes in extreme rainfall than changes in average rainfall.

CLIMATE MODEL EVALUATION, DIAGNOSIS, AND IMPROVEMENT

Recent advances in climate model evaluation and diagnostics include the use of both improved coupled climate models and new diagnostic techniques, and case studies of particular climate events—for example, the 1997-1998 El Niño. Researchers are working in a multi-faceted manner to improve climate model simulation on a hierarchy of time scales using a variety of different approaches. The information learned from these studies at all relevant time scales is being infused into the model development process. In this way, important processes that contribute to essential climate feedbacks are being addressed in a manner consistent with the recommendations made by the National Research Council in its report *Understanding Climate Change Feedbacks*. Examples of this work are provided below.

Weather Time Scale

Running climate models in weather forecast mode continues to yield useful insights. Many errors in the climate simulated by the model are the result of errors found in the short-range forecasts, making their diagnosis and improvement in this framework tractable. One such problematic aspect of many climate models is representation of the day-night (diurnal) cycle of precipitation over land. Detailed diagnostics of model simulations have been performed at the Atmospheric Radiation Measurement (ARM) Southern Great Plains site. At this site, ARM data can be used to diagnose the effects of large-scale circulation and moist processes on the diurnal characteristics of temperature and moisture.

Intraseasonal Time Scale

The Madden-Julian Oscillation (MJO) dominates tropical variability at time scales of 30 to 70 days. During the boreal winter and spring, it manifests as an eastward propagating disturbance that affects convection (rainfall) over much of the tropical eastern hemisphere. The MJO is a critical test of the ability of a climate model to correctly simulate tropical variability that most models fail to accurately represent. An improved representation of the MJO should contribute to improved medium-range and seasonal forecasts over the tropics, and possibly the extratropics. Recent analyses of models and observations indicate that simulating a realistic basic state is at least as important as air-sea interaction for producing the MJO. Additional recent analyses found that the Southeast Asian summer monsoon must be considered as a mutually interactive system with the MJO. By doing so, the onset of conditions that suppress convection (break the monsoon) over India may be detected 5 to 10 days earlier than had been previously suggested.

Interannual Time Scale

A recent study used the 1997-1998 El Niño as a test case to analyze cloud-climate interactions in a state-of-the-art climate model. This climate event was characterized by a drastic change in the tropical Pacific's atmospheric circulation, with corresponding anomalies in cloud altitudes. The study found that the model reproduced these changes well, including changes in the east-west structure of clouds. Another recent study examined the structure of warm season hydroclimate variability over the U.S. Great Plains—a region of profound importance for U.S. agriculture—and the extent to which the observed variability features are represented in state-of-the-art climate model simulations. The study found that remote water-vapor sources play an important role in generating interannual variability in the observed Great Plains summer hydroclimate. The tested models, however, largely depend on anomalies in local evaporation (precipitation recycling) to generate this variability. Further understanding of the source of the models' spurious evaporation is needed before they can be confidently used for regional hydroclimate simulations and predictions.

Centennial Time Scale

Climate modeling groups around the world performed an unprecedented set of coordinated 20th- and 21st-century climate change experiments in 2004 and early 2005, in addition to greenhouse gas stabilization experiments extending to the 22nd century (see description later in this chapter), for the IPCC Fourth Assessment Report. The resulting multi-model data set is a unique and valuable resource for international scientists to assess model performance, model sensitivity, and model response to a variety of factors related to 20th-, 21st-, and 22nd-century climate and climate change. Convenient and rapid access to this data set is provided through a specially configured web portal at the Program for Climate Model Diagnostics and Intercomparison, which includes a catalog and an interface to the archive. Over 300 projects using the archive have been registered, and over 200 manuscripts have been submitted for publication to date. The CCSP-sponsored Climate Model Evaluation Project (CMEP) supported more than 20 projects specifically to analyze the models' ability to simulate features of 20th-century climate. The list of publications that has resulted from the CMEP activity is available at <www.usclivar.org/CMEP_awards.html>.

Refer to chapter references 1,5,16,29,32,33,36,39,43,49,51,57,58 for more detail.

Estimating Future Changes in Permafrost.[24] Analysis of 21st-century climate change simulations with a state-of-the-art climate model (Community Climate System Model, CCSM3) has shown that areas of permafrost may greatly decrease over the course of the 21st century, with the area of decrease proportional to the amount of warming, which in turn depends in part on the emissions scenario used in the model. Such large changes in permafrost may provoke positive feedbacks such as activation of the soil carbon pool and a northward expansion of shrubs and forests.

Tropical Ocean Response to Global Warming.[27,52] Many studies have suggested that tropical Pacific SSTs are most likely to respond to global warming with an El Niño-like pattern, characterized by stronger warming in the east than in the west. However, a new finding from the most recent IPCC model simulations as well as past climate records challenges this traditional view. A recent study suggests that the most robust fingerprint of tropical Pacific SSTs in response to global warming is the so-called Enhanced Equatorial Response, characterized by an enhanced equatorial warming relative to the subtropics (Figure 8a). In comparison, the east–west difference in equatorial SSTs shows little systematic long-term change (Figure 8b). This new finding calls for a rethinking of the mechanism for tropical ocean response to global warming.

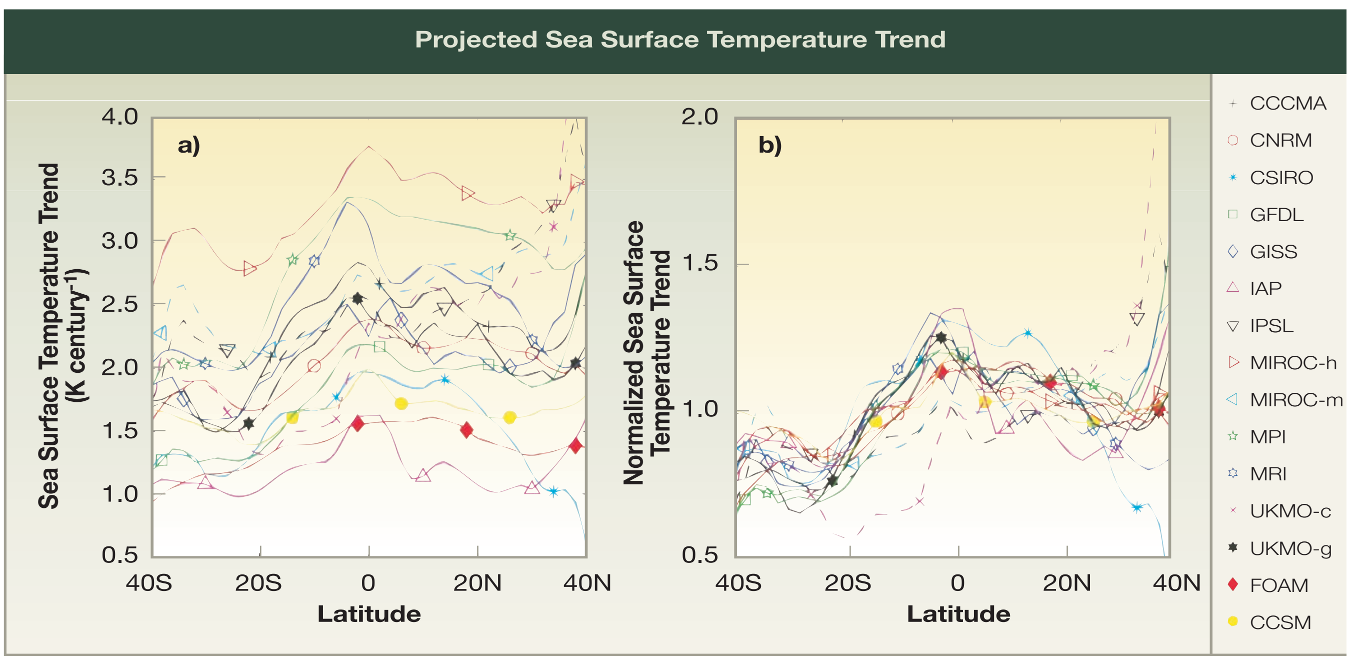


Figure 8: Projected Sea Surface Temperature Trend. Trends of Pacific sea surface temperature in IPCC model simulations driven by a transient increase in atmospheric CO_2 concentration. (a) Sea surface temperature trend averaged across the Pacific at each latitude between 40S and 40N, showing general agreement among models for enhanced equatorial warming. (b) As in (a), but with each model's temperature trend divided by each model's mean trend over the Pacific Ocean, showing the robustness of the enhanced equatorial warming across the models regardless of their individual climate sensitivities. *Credit: Z. Liu, University of Wisconsin (reproduced from the* **Journal of Climate** *with permission from the American Meteorological Society).*

DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

Two related sets of issues being addressed by CCSP are the extent and causes of recently observed changes. Research on the extent, as well as the characteristics of climate change (i.e., detection), is based on analyses of observational data from both *in situ* and remotely sensed sources and comparison with historical and proxy records. Research on the causes of climate change (i.e., attribution) is based on focused modeling and process studies. The modeling studies often use estimates of historical changes in human-caused and natural external forcings (i.e., factors that may cause climate change such as greenhouse gases, solar output, volcanic eruptions, and dust particles) to assess the relative contributions of the various forcings to the observed changes. Early analyses of this type focused primarily on globally averaged surface temperature during the past century. However, recent CCSP work has utilized a much wider range of variables and has explored a variety of new analytical techniques. Some of the climate variables that have been analyzed include regional temperature extremes, African drought, atmospheric pressure, ocean temperature, precipitation, and upper atmospheric temperature. Examples of results from some of these studies are outlined below.

European Heat Wave

The summer of 2003 was probably the hottest in Europe since at least AD 1500, and unusually large numbers of heat-related deaths were reported in France, Germany, and Italy. It is not possible to definitively determine whether the 2003 heat wave was caused by, for example, increasing atmospheric concentrations of greenhouse gases, since almost any such weather event might have occurred by chance in an unmodified climate. However, it is possible to estimate how much human activities may have increased the risk of the occurrence of such a heat wave. Using a threshold for mean summer temperature that was exceeded in 2003, but in no other year since the start of the instrumental record in 1851, a modeling study recently concluded that it is very likely (confidence level >90%) that human influence has at least doubled the risk of a heat wave exceeding this threshold magnitude. Model projections of future climate change indicate that summers as warm as that of 2003 in Europe are likely to be typical by 2040.

African Drought

Two recent studies have strongly implicated long-term variations in ocean conditions in producing prolonged drought conditions in the Sahel and portions of central Africa during the latter part of the 20th century. One study analyzed 80 separate 50-year climate simulations from a suite of climate models in which the only external driving force was observed SST. The results showed a very robust response across all models in reproducing the observed precipitation patterns over Africa during this period. The drying over the Sahel during boreal summer was shown to be a response to warming of the South Atlantic relative to the North Atlantic during this period, which favored a southward shift of the ITCZ and accompanying rainfall. That study also evaluated a set of greenhouse gas-forced experiments conducted for this period as part of the IPCC Fourth Assessment Report. The authors found that, while there were considerable differences among the model simulations, the majority were unable to simulate either the pattern or amplitude of the 20th-century African drying, leading them to conclude that the observed, sustained African drought conditions were most likely due to long-period, natural variations in Atlantic ocean conditions, rather than to greenhouse gas forcing.

A second study with a coupled climate model forced with greenhouse gases was, however, able to reproduce much of the observed African precipitation variability. As in the first study, Atlantic SST variations were found to be important in causing the Sahelian drought, but in this model, the SST changes resulted largely from changes in the north-south distribution of aerosols during this period. The authors of this second study suggested that anthropogenic as well as natural factors might have caused the 20th century Sahelian drought. Because of the wide range of coupled model projections of future SST distributions in the North and South Atlantic, projections of future precipitation in this region remain uncertain. These studies and others reinforce the need for improved understanding of sources of variability in the world oceans to increase confidence in projections of future regional climate changes.

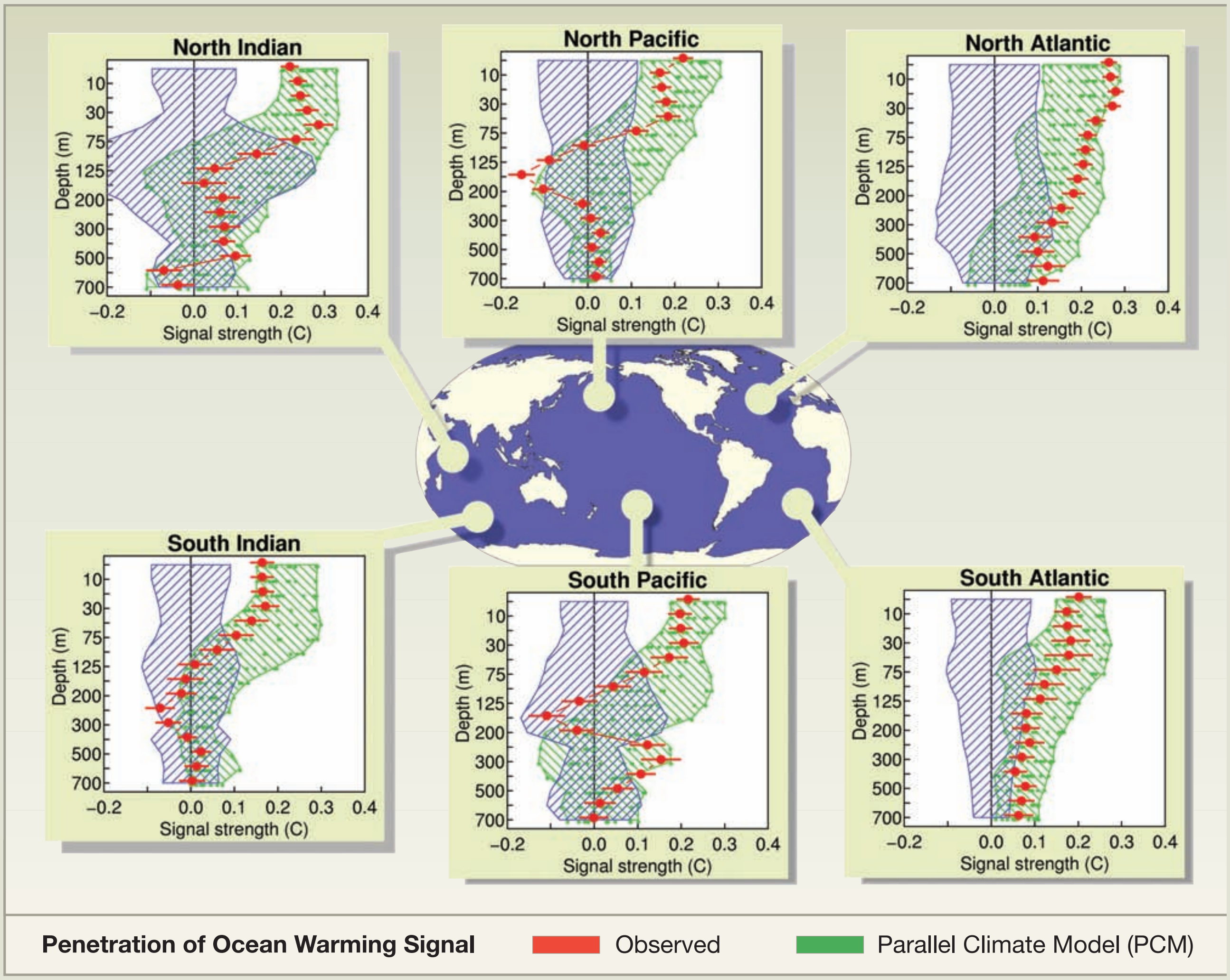
North American Droughts and Wet Periods

Recent research suggests that subtle, prolonged changes in SSTs in the tropical oceans, especially in the tropical Pacific Ocean, may have been responsible for prolonged North American droughts and pluvials (extended periods of abundant rainfall) in the 19th and 20th centuries. This new work highlights links between decadal variability of tropical Pacific SSTs and major, high-impact events such as the 1930s Dust Bowl drought, drought in the 1950s, the pluvial period in the late 20th century in the western United States, and the return to drought in this region after 1997. The relationships were investigated using a large ensemble of 145-year climate model runs.

Ocean Temperature

Observations show that approximately 84% of the total heating of the Earth system (oceans, atmosphere, continents, and cryosphere) over the last 40 years has gone into warming the oceans. A recent study on the vertical structure of ocean warming trends over the past 40 years

DETECTION AND ATTRIBUTION OF CLIMATE CHANGE (CONTINUED)



Warming Signal by Ocean/Depth. Anthropogenic forcing signal strength (green hatched region) compared to that obtained from observations (red dots). There is excellent agreement at most depths in all oceans. The hatched region shows the range of the signal strength estimates from five different realizations of identically forced simulations with the Parallel Climate Model. *Credit: D. Pierce, Scripps Institution of Oceanography (reproduced with permission from* **Science***).*

in various basins compared trends in climate model simulations with trends based on an updated ocean temperature data set. The warming signal is complex, with a vertical structure that varies widely by ocean. It cannot be explained by natural internal climate variability or solar and volcanic forcing, but is relatively well simulated by two anthropogenically forced climate models (see accompanying figure).

Another study examining the warming in the oceans over the last century suggests that, in addition to greenhouse gases, aerosols (tiny airborne particles) have played a significant role during this period. Aerosols may have delayed the onset of warming by several decades and reduced the magnitude of the warming by approximately two-thirds when compared to the response arising solely from increasing greenhouse gases.

Refer to chapter references 2,3,8,12,17,19,21,22,26,47,50 for more detail.

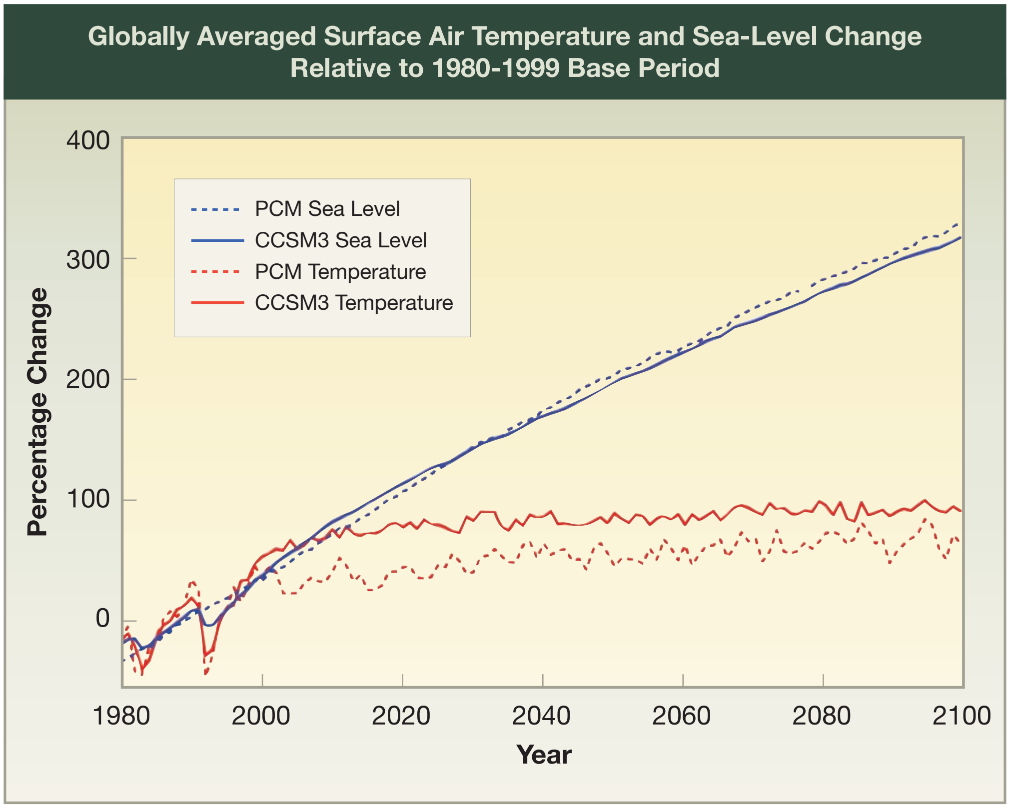


Figure 9: Globally Averaged Surface Air Temperature and Sea-Level Change Relative to 1980-1999 Base Period. Results from two state-of-the-art climate models (the Parallel Climate Model and the Community Climate System Model) in which greenhouse gas concentrations are stabilized at the end of the 20th century. Temperature and sea-level values are shown relative to the averages for the base period, 1980-1999. *Credit: J. Arblaster, National Center for Atmospheric Research (reproduced with permission from* ***Science****).*

Climate Model Studies with Static Greenhouse Gas Concentrations.[34] A greenhouse gas stabilization experiment performed with two global climate models (the Parallel Climate Model and the CCSM3) shows that even if concentrations of greenhouse gases could be stabilized at present-day values, the thermal inertia of the climate system would lead to further warming, and ongoing sea-level rise due to thermal expansion of seawater. These modeling results indicate that if greenhouse gas concentrations were stabilized at present levels, by 2100 sea level may rise about three times the amount that has already been observed (see Figure 9), with continued sea-level rise for a few subsequent centuries.

HIGHLIGHTS OF FY 2007 PLANS

Development of Integrated Earth System Analysis Capabilities. Research across several agencies will focus on supporting the development of a national capacity to provide integrated Earth system analyses, in order to provide an ongoing, near-real-time basis for assessing the state of the global Earth system. Initially, these analyses will be performed at a variety of temporal and spatial scales and with different degrees of coupling between components of the Earth system (e.g., carbon cycle, ocean, water cycle, ecosystems). In future years, as observing systems and models improve, this capacity will be supported by periodic integrated Earth system reanalyses to serve as the Nation's best assessment, or "analysis of record," of how the Earth system has varied over the recent historical period. These efforts will directly support vitally important scientific linkages between current and proposed future Earth observation systems and Earth system modeling capabilities.

These activities will address Goals 1 and 2 of the CCSP modeling strategy, Goal 4 of the CCSP observing and monitoring strategy, and Questions 4.1 and 4.2 of the CCSP Strategic Plan.

Modern Era Retrospective-analysis for Research and Applications (MERRA). MERRA is a specific example of the work being conducted on the priority item mentioned above: development of integrated Earth system analysis capabilities. The purpose of the MERRA project is to develop, validate, and disseminate a global retrospective analysis data set, covering the modern era of remotely sensed data from 1979 through the present. The special focus of the atmospheric assimilation project will be the hydrologic cycle. This project is expected to take 2 years to complete (see <gmao.gsfc.nasa.gov/research/merra>).

This activity will address Goals 1 and 2 of the CCSP modeling strategy and Questions 4.1 and 4.2 of the CCSP Strategic Plan.

Carbon Data Assimilation (CDA). Another specific example of integrated Earth system analysis work is a 5-year effort to develop a coupled Earth system assimilation model for carbon and ecosystems. The first stage commenced in FY 2006, when a NASA atmospheric model (GEOS5) together with a NOAA assimilation scheme was installed on computers at the Oak Ridge National Laboratory to begin testing. The GEOS5 model is compliant with Earth System Model Framework standards, which is important for exchanging and intercomparing model elements. This activity is part of DOE's National Leadership Computing Facility (NLCF) Climate End Station climate and carbon research. Future plans include coupling several different ocean models to

the GEOS5 atmosphere, as well as to a dynamic ecosystem model. With launch of the NASA Orbiting Carbon Observatory (OCO) satellite scheduled in 2008, this model integration and evaluation will improve the characterization of carbon sources and sinks.

These activities will address Goals 1, 2, and 3 of the CCSP modeling strategy, Goal 2 of the CCSP Strategic Plan, and Questions 3.5, 4.1, 4.2, and 7.5 of the CCSP Strategic Plan.

Earth System Response to Climate Change and Variability. Research will be conducted on the response of terrestrial, wetland, estuarine, and marine systems to climate changes at seasonal to millennial time scales using paleoclimatic proxies of past climate variability. These process-based studies are designed to understand the physical, biological, and chemical impacts of different climate regimes, as well as leads and lags between different climate events and Earth system responses. Paleoclimatic observations provide insights into mechanisms governing climate change and variability at regional to global scales and key information to improve predictions of future Earth system response to a variety of climate and environmental changes. These data will also provide a context for evaluating data generated through emerging integrated Earth system analysis capabilities.

These activities will address Goals 1 and 4 of the CCSP Strategic Plan and Questions 4.2, 4.3, 4.4, and 8.2 of the CCSP Strategic Plan

Database of Arctic Climate Variability. A new database will be completed of Arctic climate variability derived from paleoclimate proxies spanning the past 2,000 years. The project synthesizes the results of dozens of studies funded by NSF and other sources, with the aim of reconstructing long-term variations in Arctic temperature, as well as reconstructing the natural variability that exists in temperature, precipitation, sea-ice extent, surface pressure, and other environmental parameters over shorter time periods (see <www.ncdc.noaa.gov/paleo>).

This activity will address Goal 1 of the CCSP Strategic Plan and Questions 4.1, 4.2, 4.3, and 4.4 of the CCSP Strategic Plan

New Integrated Ocean Drilling Program to Obtain High-Resolution Climate Records. The first phase of the Integrated Ocean Drilling Program produced high-resolution records of climate over past millennia from marine sediments. Recent examples include the first recovery of central Arctic Ocean marine sediment records and expeditions to drill methane hydrates, which may have been a cause of past abrupt climate change. The Integrated Ocean Drilling Program will enter a new phase of operations in FY 2007 with a major refit and conversion of the JOIDES *Resolution*, a dedicated scientific ocean drilling vessel used for recovering sequences of sediment and rock cores from global ocean basins (depicted in Figure 10). When the refit and conversion is complete, the international research community will have a multi-platform marine drilling capability, including the *Resolution* (a light drill ship) and the *Chikyu* (a heavy drill ship provided by Japan), to retrieve new and longer records of climate change from the deep seafloor in a new era of scientific drilling. Rapidly accumulating marine sediments remain the longest, most continuous record of past climate and environmental variability found on the planet and will be explored by the *Resolution*.

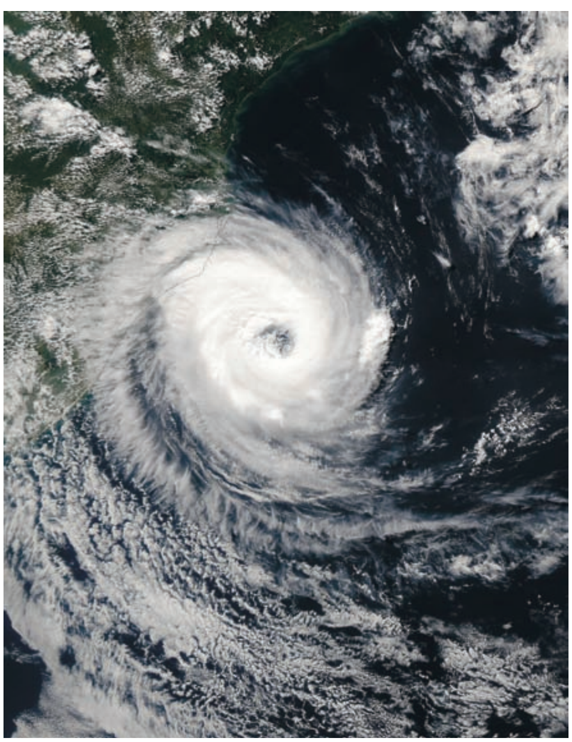
This activity will address Goals 2 and 5 of the CCSP observing and monitoring strategy and Question 4.3 of the CCSP Strategic Plan.

Figure 10: Integrated Ocean Drilling Platform. The dedicated JOIDES *Resolution* scientific drilling vessel used for recovering sequences of sediment and rock cores from global ocean basins. *Credit: D. Anderson, NOAA/National Geophysical Data Center.*

NARCCAP Data Analysis Phase. The North American Regional Climate Change Assessment Program (NARCCAP) is part of a U.S.-Canadian/European collaborative regional climate modeling study. NARCCAP's primary objective is to develop, and make openly available, multiple high-resolution regional climate change scenarios for use in impact and risk assessments. Analyses of the scenarios, with a focus on North America, will be conducted in FY 2007 to: (1) understand critical regional climate change issues, such as the effects of increased greenhouse gases on the frequency of various types of extreme weather events; (2) enhance understanding of key issues in regional climate modeling, including methodological approaches; (3) conduct a limited examination of uncertainties in regional and global climate model projections; and (4) create greater collaboration between U.S., Canadian, and European climate modeling groups to leverage the diverse modeling capability across these nations.

These activities will address Goals 4 and 5 of the CCSP Strategic Plan and Questions 4.3 and 4.4 of the CCSP Strategic Plan.

Reducing Tropical Errors in Climate Models. A multi-institutional project will continue in FY 2007 to attempt to reduce errors in the tropics in coupled ocean-atmosphere general circulation models. These errors affect the average SST and precipitation as well as the structure and distribution of climate variability throughout the tropics, and must be significantly reduced for coupled general circulation models to realize their potential for climate prediction. This project began with an initial workshop held at NOAA's Geophysical Fluid Dynamics Laboratory in 2003 and a second workshop at the Center for Ocean-Land-Atmosphere Studies (COLA) in 2005. At the COLA workshop, several experiments were agreed on, and progress was reviewed in June 2006 at the annual Community Climate System Model workshop. Descriptions of the first and second workshops and ongoing work are available at <www.iges.org/ctbp>.



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

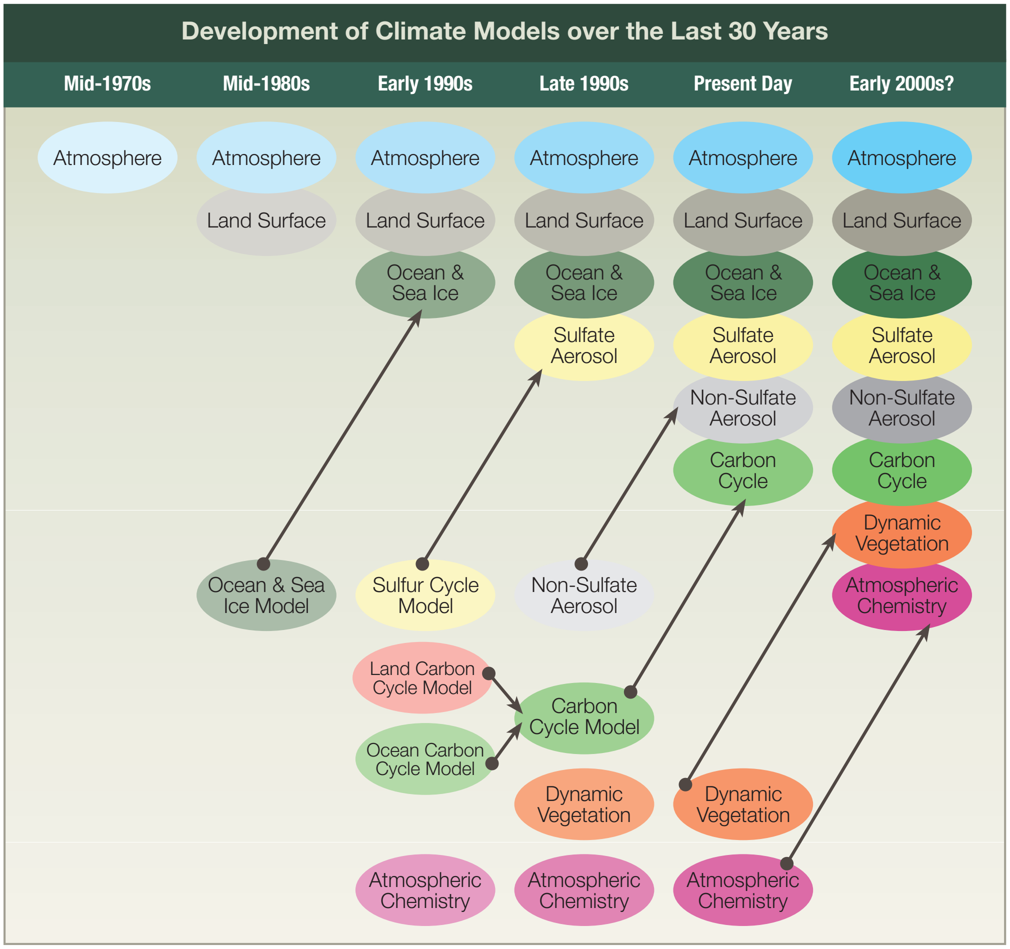
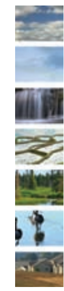


Figure 11: Development of Climate Models over the Last 30 Years. The development of climate models over the last 30 years showing how the different components are first developed separately and later coupled into comprehensive climate models. *Credit:* **CCSP Strategic Plan**, *Chapter 10 (2003).*

Development of the Next Generation of Climate System Models. In parallel with continued research on the physical representations of climate processes, particularly in the tropics, climate model development will concentrate on improving representations of aerosols, atmospheric chemistry, the carbon cycle, land surface-atmospheric processes, and middle-atmosphere dynamics and chemistry (Figure 11 describes the development of climate models over the past 30 years). The products will be next-generation climate system models with enhanced capabilities to model more comprehensively the interactive physical, chemical, and biological components of the climate system. This work will continue over the longer term, leading to fully interactive Earth system models.

These activities will address Goal 1 of the CCSP modeling strategy,
Goals 1, 2, and 3 of the CCSP Strategic Plan,
and Questions 4.1 and 4.2 of the CCSP Strategic Plan.



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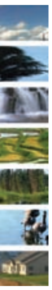

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