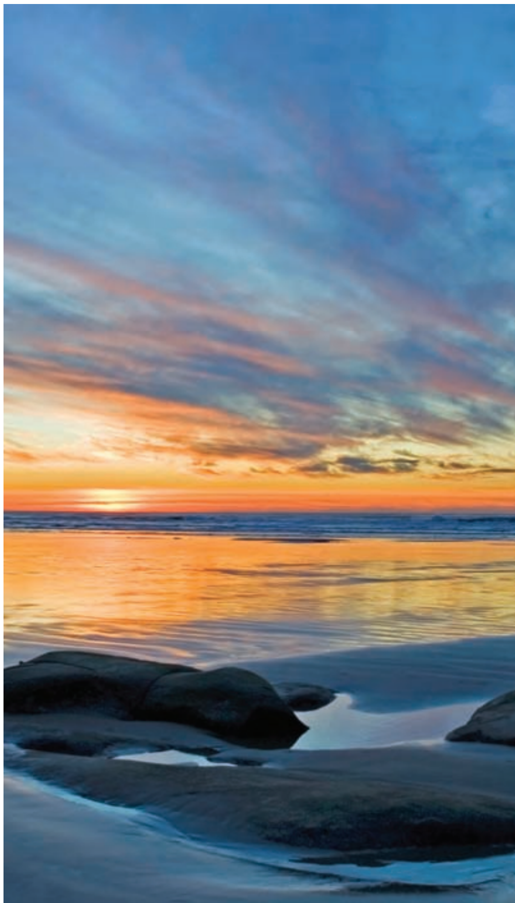


2 | Climate Variability and Change

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.

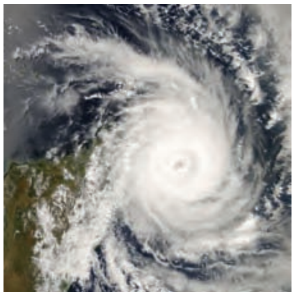
To address fundamental CCSP goals, the climate variability and change (CVC) element emphasizes research to improve descriptions and understanding of past and current climate, as well as to advance national modeling capabilities to simulate climate and project how climate and related Earth systems may change in the future. Research under this element encompasses time scales ranging from short-term climate variations of a season or less to longer term climate changes occurring over decades to centuries. The CVC element places a high priority on improving understanding and predictions of phenomena that may cause high impacts on society, the economy, and the environment. Examples include identifying the relationships between variations and changes in climate and hurricane activity; improving understanding and predictions of droughts; increasing understanding of and capabilities to predict the El Niño-Southern Oscillation and its attendant impacts; identifying processes that may produce rapid or accelerated climate change; and improving capabilities to observe, understand, and model Earth system components that have high societal and environmental relevance, including sea ice, glaciers, ice sheets, and sea level. Addressing these fundamental issues requires an integrated approach toward understanding the interactions and feedbacks among the different components of the Earth system, including the atmosphere, ocean, land, cryosphere, and biosphere.

CVC research is placing increasing emphasis on understanding and modeling the links and feedbacks among climate system components. Considerable advances have been made in this area through the development and application of Earth system models, including several that were used extensively in the recently completed Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (see introductory chapter of this report). CVC research is also emphasizing the development of new capabilities to link Earth system models together with Earth system observations to produce internally consistent maps of atmospheric, oceanic, land surface, and ice conditions that are called "Earth system analyses." These analyses will help us to understand and explain past and current climate conditions, and provide decisionmakers with new tools to track how the Earth system is evolving in time over the entire planet.

Research within the CVC element focuses on two broad, critically important questions to society defined in the CCSP Strategic Plan:

- 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 at the beginning of this chapter to achieve the milestones, products, and payoffs described in the CCSP Strategic Plan. Cooperative efforts involving CCSP agencies have led to significant progress in addressing the strategic questions articulated in the CVC chapter of the CCSP Strategic Plan. The following section highlights some of the major scientific advances achieved during this past fiscal year.

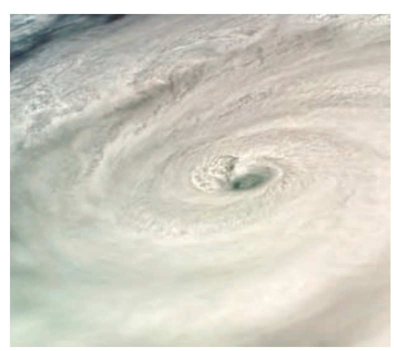


Highlights of Recent Research

This year's highlights of climate variability and change research emphasize advances in several areas of high societal interest. These include improving understanding of tropical cyclone-climate links; droughts; the predictability of the El Niño-Southern Oscillation; changes in the North Atlantic Ocean circulation; ice processes and implications for sea-level changes; the causes of sea ice declines; and detection and attribution of the causes for regional climate changes, including effects of air pollution on Asian climate.

Assessing Tropical Cyclone-Climate Links from Paleoclimate Data.[1,2] A new line of research is applying paleoclimate data to study tropical cyclone behavior before the period of modern observational records, a field called "paleotempestology." This research provides the potential to study climate-tropical cyclone relationships through a wider range of climates than can be obtained from the modern observational period. By greatly increasing the time interval under consideration, this approach also enables the possibility of detecting rare, catastrophic events that have very long recurrence intervals (hundreds of years or longer). Using marine sediment cores and corals, two recent studies have quantified the frequency of major hurricanes in the North Atlantic over the past 5,000 years. They find that the frequency of major hurricanes has varied on centennial to millennial time scales; however, a simple relationship to sea surface temperature variations seems to be lacking. These studies suggest the potential importance of other factors, such as variations in the El Niño-Southern Oscillation, tropical monsoons, and trade wind strength in determining variations in the strength of hurricanes.

Climate-Hurricane Links Over the North Atlantic.[3,4,5,6] Vigorous scientific debate continues about the detection of trends in Atlantic hurricane activity, with several studies published within the past year giving conflicting findings. One recent study showed a strong positive correlation between multi-decadal sea surface temperature variations and tropical cyclone counts and concluded that a trend toward increasing numbers of tropical cyclones in the Atlantic basin has been driven predominantly by anthropogenically forced increases in Atlantic sea surface temperatures. In contrast, another study suggested that the estimated increase in the number of Atlantic hurricanes over the 20th century is mostly, if not entirely, due to observational uncertainties that lead to substantial storm undercounts early in the period. Yet another study argues that a trend toward increasing Atlantic hurricane activity is insensitive to a range of estimates of storm undercounts. Efforts continue to reanalyze



the tropical cyclone record, as well as the climate of the early part of the 20th century. This work should improve ability to describe and understand the causes of climate-hurricane relationships.

Modeling Studies of Climate Factors Influencing Hurricanes.[7,8] Recent research on Atlantic hurricanes and climate change has focused on whether the increase in hurricane activity in the basin since the 1970s portends future large increases in a warming climate. In an analysis of projected climate changes over the tropical Atlantic region during the 21st century derived from 18 different climate models developed for the IPCC Fourth Assessment Report, a notable finding was that the vertical wind shear (the difference in wind direction and speed between the lower and upper atmosphere) is projected to increase across much of the Caribbean in the warmer climate, a factor that tends to suppress tropical storm and hurricane development and intensification. In other basins, shear was reduced, which would tend to favor enhanced tropical storm activity. This study emphasizes the importance of incorporating changes in vertical wind shear as well as sea surface temperatures in projections of future hurricane activity.

A second study introduced a new regional modeling approach for understanding mechanisms that produce changes in Atlantic hurricane activity. The study uses a high-resolution model (18-km, or about 11-mile grid spacing) in which the large-scale atmospheric conditions are provided from historical analyses ("reanalyses") and ocean conditions are derived from observed sea surface temperatures. Within the evolving large-scale state, the model generates hurricane activity. This method successfully models the observed increase in Atlantic hurricane activity over the period 1980 to 2006, as well as other features like diminished hurricane activity during El Niño years. This new approach should provide an important means for addressing key questions regarding possible responses of Atlantic hurricane activity to future climate warming.

Climate Model Projections of Increasing Aridity in Southwestern North America.[9] A recent study examines how the hydroclimate over southwestern North America may change over the remainder of this century. The study evaluates climate change projections out to 2100 derived from 19 climate models used in the IPCC Fourth Assessment Report. These models were forced with the A1B emissions scenario, in which carbon dioxide (CO_2) emissions increase until about 2050 and then decrease modestly. The study shows that 18 of the 19 models predict a drier climate for the southwest United States. The projected trend in "precipitation minus evaporation," an indicator of drought potential (see Figure 6), implies that droughts as severe as the 1930s Dust Bowl drought may become common occurrences in this region within the next few decades.

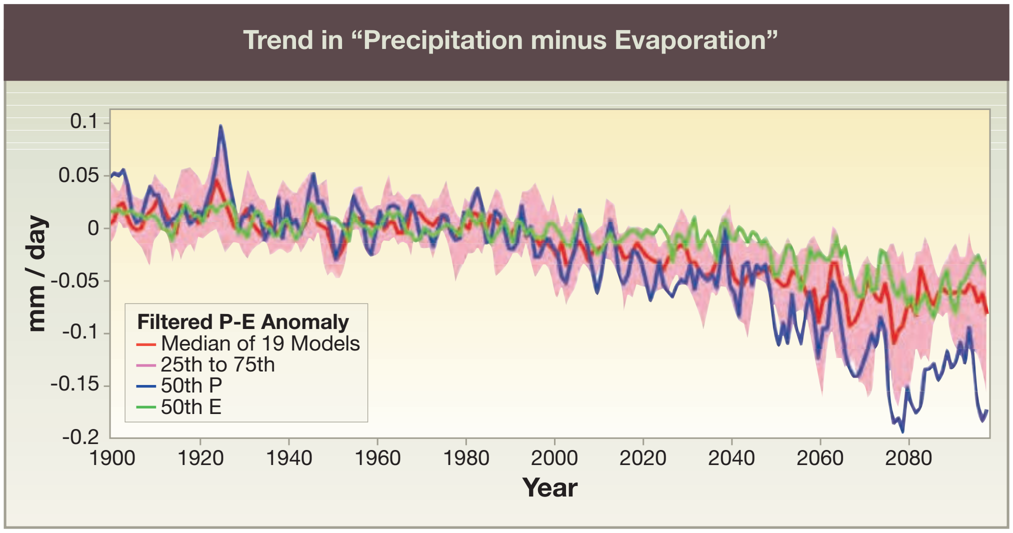
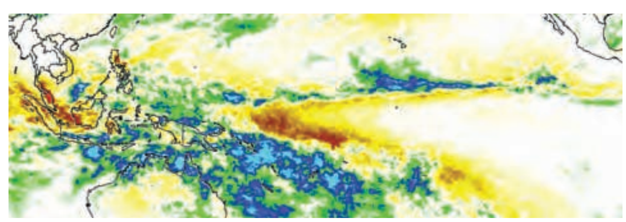


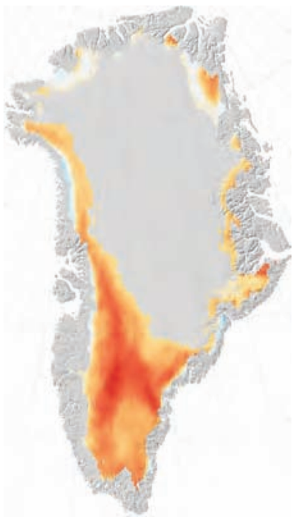
Figure 6: Trend in "Precipitation minus Evaporation". The trend in "precipitation minus evaporation" for the southwest United States simulated by the climate models used for the IPCC Fourth Assessment Report. *Credit: R. Seager, Lamont Doherty Earth Observatory (reproduced from* **Science** *with permission from the American Association for the Advancement of Science).*

The projections suggest that rain-producing storms that normally affect the southwest United States will shift northward, making the region drier. Further work will be required to understand the reason for the shifts in the storm patterns.

Seasonal-to-Interannual Predictability of the Tropical Pacific and Atlantic.[10,11,12] A debate currently exists about the extent to which the predictability of the El Niño-Southern Oscillation (ENSO) is limited by uncertainties in specifying initial conditions or by errors associated with "weather noise" and other unresolved physical processes. Understanding what limits climate predictability is critical to quantifying confidence in ENSO predictions and related impacts over North America. Recent research, using a new interactive ensemble coupling strategy, suggests the skill of current operational ENSO forecasts is limited mainly by initial condition errors. Other sources of error, however, do have a significant impact on the predictability of La Niña events and large El Niño events. For the tropical Atlantic sector, research is exploring the impact of biases in model simulations on their ability to reproduce and predict the leading patterns of climate variability in this region, with the goal of improving operational seasonal forecasts.



New Observations of the North Atlantic Ocean Circulation.[13,14] An issue of major concern is the potential for rapid and dramatic collapse of the northward flow of warm water in the North Atlantic, which may have serious implications for the climate of surrounding regions, including North America and Europe. A new international observing program, partly supported by U.S. agencies, is examining whether and how this flow is changing. The northward flow of relatively warm, near-surface water is closely linked to a southward flow of cold, deep water, which forms an oceanic conveyer belt called the Atlantic Meridional Overturning Circulation (AMOC). Two recent studies report on observations of the variability in the AMOC, which is a fundamental prerequisite to understanding trends in this circulation, as well as its potential for rapid collapse. The studies indicate surprisingly large variability over the course of the 1-year period for this new program, suggesting that trends detected in previous studies from "snapshot" observations may be strongly influenced by the sampling of this large intra-annual variability. Observations from this program appear to be of sufficient accuracy to detect any large abrupt transition of the AMOC. The short period of record precludes a description of how the AMOC varies interannually. Understanding this variability will be critical for improving climate models used in predictions and projections of climate variability and change.



Ice Processes and Sea Level Change.[15,16,17] Future sea-level rise will depend on how much the ocean expands from future warming, as well as ice loss to the sea from glaciers, ice caps, the larger Greenland and Antarctic Ice Sheets, and other factors. A recent study found that about 60% of the ice loss in recent years has been from glaciers and ice caps (features whose perennial snow and ice coverage is less than 50,000 km^2) rather than the larger ice sheets. Acceleration of glacier melt, in part due to processes not yet considered in models, may cause an additional 0.1 to 0.25 m of sea-level rise by 2100. An analysis of Special Sensor Microwave/Imager (SSM/I) radiometer measurements over the Greenland Ice Sheet back to 1988 shows that there was an extended period of melting snow in 2006, with snowmelt occurring more than 10 days longer than the 1988-2005 average over certain areas. Yet another separate analysis using satellite-derived surface elevation data found major variations in recent ice discharge and mass loss at two of Greenland's largest outlet glaciers. These studies point to the need to better constrain observations and advance understanding of ice outlet dynamics in order to improve projections of future sea-level rise. As noted in the IPCC Fourth Assessment Report, there are presently large uncertainties about the processes controlling ice flows, and advances in this area will be critical to improving models required for estimating future sea-level rise.

Declines in Arctic Sea Ice.[18,19] There have been dramatic declines in Arctic sea ice in recent decades that are particularly strong in summer and early fall (Figure 7), but are evident throughout the year. A study compared observations against sea ice simulations from more than a dozen models that were used in the IPCC Fourth Assessment Report. The results indicated that nearly all the models failed to produce as much of a decrease in minimum Arctic sea ice coverage as was observed, often substantially underestimating

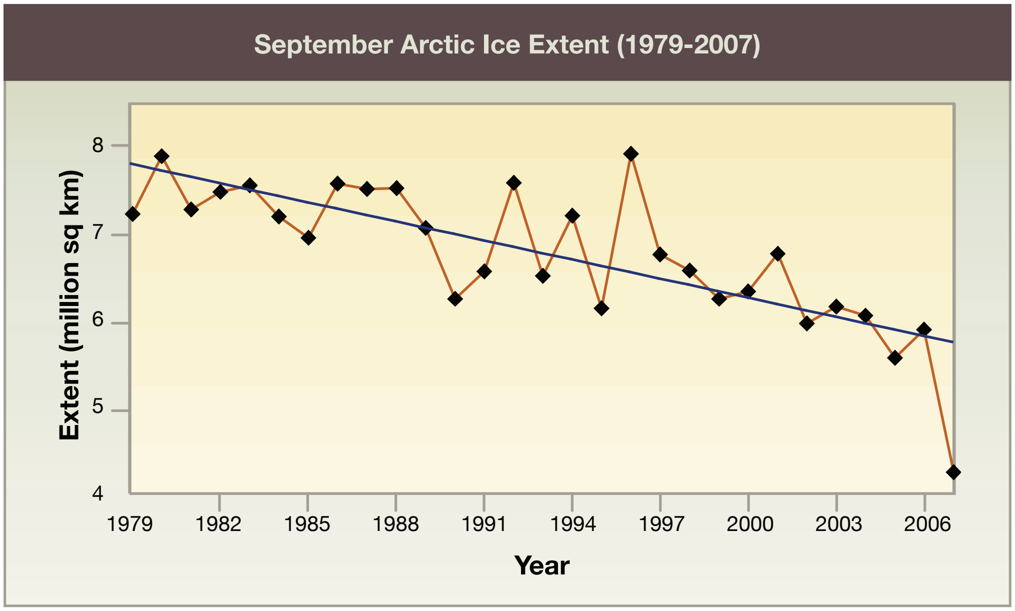
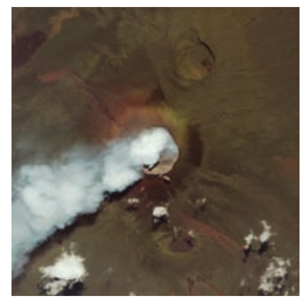


Figure 7: September Arctic Ice Extent (1979-2007). September sea ice extent across the Arctic from 1979 to 2007. The September rate of sea ice decline since 1979 is now approximately 10% per decade, or 72,000 km^2 yr^{-1}. *Credit: National Snow and Ice Data Center.*

the decreases. The authors suggest that the Arctic could be seasonally free of sea ice earlier than IPCC projections. Another study considered factors that may contribute to declines in sea ice in the Arctic winter. The results show important regional differences in the processes leading to the changes, although the hemispheric-mean decline in winter ice extent appears primarily due to increasing sea surface temperatures in the Barents Sea and adjoining waters. This result is in contrast to earlier work showing that downwelling longwave radiation is the leading factor contributing to changes in Arctic minimum sea ice extent in late summer and early fall, although relative contributions from different factors vary by region and year. The results emphasize the important roles of both atmospheric and oceanic processes in understanding and modeling the causes of rapid sea ice declines.

Detection of Human Influence on 20th Century Precipitation Trends.[20,21,22] Human influence on climate has been detected in numerous quantities, but changes in precipitation have been more difficult to attribute to human causes, partly due to sampling errors associated with inferring global precipitation trends from the archive of mostly land-based measurements. Two recent studies shed new light on this detection problem. One study makes use of monthly precipitation observations over global land areas for 50 to 75 years prior to 2000 and demonstrates that anthropogenic forcing has had a detectable influence on observed changes in average precipitation within latitudinal bands. In particular, anthropogenic forcing has contributed significantly to observed increases in precipitation in the Northern Hemisphere mid-latitudes, drying in the Northern Hemisphere subtropics and tropics, and moistening in the Southern Hemisphere subtropics and deep tropics. These opposing zonal trends help explain why detecting and explaining a net global trend has been so challenging. Satellite observations of precipitation reduce sampling errors but are available for a more limited period of time. In a second study, satellite observations are used to show a globally averaged increase in evaporation, precipitation, and total water of about 1.3% per decade for the period July 1987 to August 2006. During that time period, satellite measurements showed a positive trend in the globally averaged surface and lower atmosphere temperatures of about 0.2°C per decade, implying an increase in evaporation, precipitation, and total water of about 6.5% per °C. These increases in evaporation and total water agrees with climate models, but the models predict that global precipitation will increase at a much slower rate of 1-3% per °C. The reason for the discrepancy between satellite observations of precipitation and models is not clear.

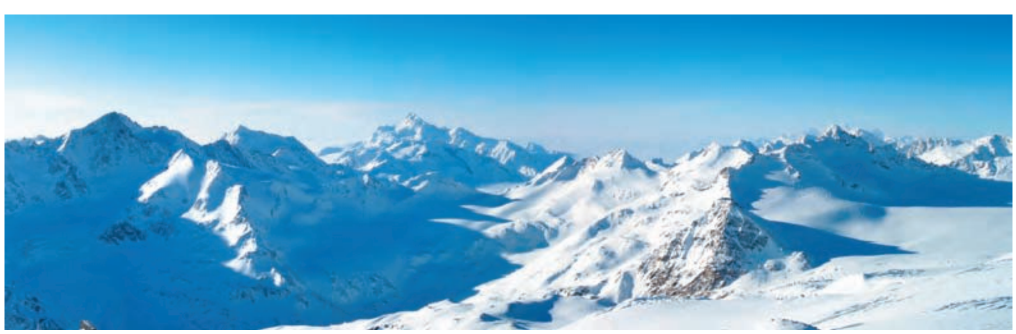


Identifying a Human "Fingerprint" Pattern in Atmospheric Water Vapor Changes.[23] Water vapor feedbacks are likely to play a key role in determining the magnitude of climate changes over the next century. Data from the satellite-based SSM/I show that the total atmospheric moisture content over oceans has increased by 0.41 kg m^{-2} per decade since 1988. Current climate models indicate that water vapor increases of this magnitude cannot be explained by natural variability alone. In a formal detection and attribution analysis using the pooled results from 22 different climate models, the simulated "fingerprint" pattern of anthropogenic changes in water vapor is identifiable with high statistical confidence in the SSM/I data. Experiments have been conducted in which forcing factors related to greenhouse gases, solar radiation, and volcanic eruptions are varied individually. The study found a decrease in water vapor levels due to cooling induced by massive volcanic eruptions (e.g., Pinatubo in 1991). The "fingerprint match" of the observed levels of water vapor indicates that the increases are primarily due to human-caused increases in greenhouse gases and not to solar or volcanic forcing. The findings provide evidence of an emerging anthropogenic signal in the moisture content of Earth's atmosphere.

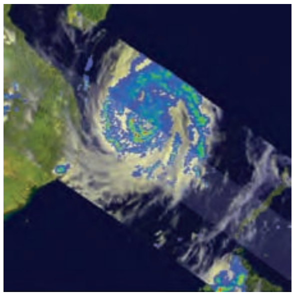
Assessing the Causes of Global Stratospheric Temperature Changes.[24] The substantial cooling of the global lower stratosphere between 1979 and 2003 occurred in two pronounced step-like transitions. These arose in the aftermath of two major volcanic eruptions, with each cooling transition followed by a period of relatively steady temperatures. Climate model simulations demonstrate that the space-time structure of the observed cooling is largely attributable to the combined effect of changes in both anthropogenic factors (ozone depletion and increases in well-mixed greenhouse gases) and natural factors (solar irradiance variation and volcanic aerosols). The anthropogenic factors drove the overall cooling during the period, while the natural ones modulated the evolution of the cooling. The quantitative understanding of the global-mean lower stratospheric temperature evolution, including the distinct roles of the different forcing agents, is now at a high confidence level.

Black Carbon Impacts on the Asian Monsoon.[25] There is a growing awareness that black carbon aerosols, with their properties of both absorbing and reflecting solar radiation, may be contributing to significant climate change in the Indian monsoon region of south Asia. To address this problem, a six-member ensemble of 20th-century simulations with changes to only time-evolving global distributions of black carbon aerosols in a global coupled climate model was analyzed to study the effects of black carbon aerosols on the Indian monsoon. The black carbon aerosols increase lower tropospheric heating over south Asia and reduce the amount of solar radiation reaching the surface during the dry season. The increased north-south tropospheric temperature gradient in the pre-monsoon months of March, April, and May, particularly between the elevated heat source of the Tibetan Plateau and areas to the south, contributes to enhanced precipitation over India in those months. With the onset of the monsoon, the reduced surface temperatures in the Bay of Bengal, Arabian Sea, and over India that extend to the Himalayas act to reduce monsoon rainfall over India itself, with some small increases over the Tibetan Plateau. During the summer monsoon season, the model experiments show that black carbon aerosols have likely contributed to observed decreasing precipitation trends over parts of India, Bangladesh, Burma, and Thailand.

Potential Impacts of Future Temperature Changes on Tropical Glaciers.[26,27,28] Recent studies have considered the potential impact of future climate warming on tropical glaciers in the Americas, which provide a vital source of fresh water (as well as hydropower) for local communities. One study examines projected changes in mean annual free-air temperatures between 1990 to 1999 and 2090 to 2099 along a section of the American Cordillera from Alaska to Chile. The results show a general tendency toward increased warming at higher altitudes, with maximum temperature increases projected to occur in the high mountains of Peru, Bolivia, and northeast Chile. Such changes would have major consequences for mountain glaciers and for communities that depend on glacier meltwater for their water supplies. Because the Andean region has become highly dependent on hydropower (comprising over 50% of total energy supply in Ecuador and about 80% in Peru), rapid glacier retreat in the Andes also has substantial economic implications for the region.



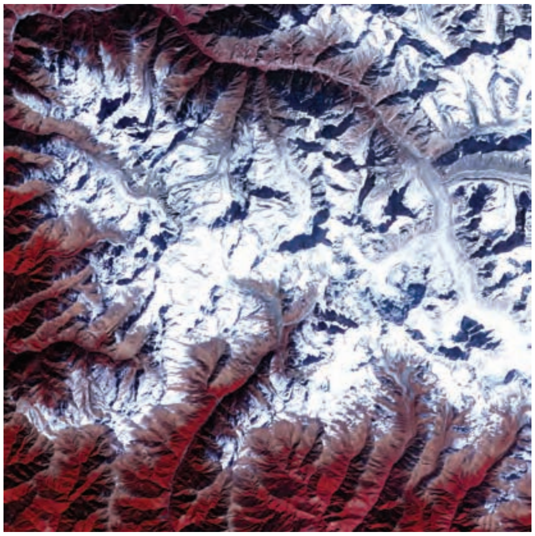
Highlights of Plans for FY 2009



Completing a Historical Reanalysis of the Atmosphere for the 20th Century. CCSP research has shown the feasibility of using modern data assimilation techniques together with observations of sea level pressure to produce a global analysis of tropospheric weather patterns at 6-hour temporal resolution for periods prior to the advent of extensive upper-air observations around 1950. Production of this first historical reanalysis will be completed in 2009. This reanalysis will provide, for the first time, a high-temporal resolution objective analysis of tropospheric weather and climate conditions over the entire 20th century. This historical reanalysis will help researchers address questions about the range of natural variability of high-impact events like floods, droughts, hurricanes, and extratropical cyclones, and how ENSO and other climate modes alter these events. This reanalysis will also help to clarify the origins of climate variations that produced major societal impacts and profoundly influenced policies, including the 1930s Dust Bowl drought and the prolonged cool, very wet period in the western United States early in the 20th century that led to over-allocation of Colorado River water through the 1922 Colorado Compact.

This activity will address Goals 1 and 3 and Questions 4.2, 4.4, and 4.5 of the CCSP Strategic Plan.

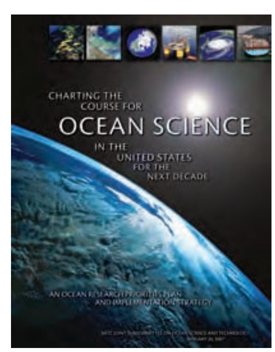
Developing a National Capacity for Integrated Earth System Analysis. CCSP continues to place high priority on developing a national capacity for integrated Earth system analysis that will enable scientists to better understand interactions among Earth system components that may produce rapid or unexpected climate changes, as well as high-impact weather and climate events. Achieving this capability requires parallel advancements in coupled Earth system modeling and the ability to assimilate Earth system observations into models. A coupled ocean-atmosphere-land-ice model will serve as the basis for developing a reanalysis of the evolution of these Earth system components over the period of extensive satellite observations from 1979 to the present. This reanalysis will also help support research and modeling capabilities required to improve seasonal-to-interannual climate forecasts.



This activity will address Goals 1 and 3 and Questions 4.2, 4.4, and 4.5 of the CCSP Strategic Plan.

Advancing Understanding of the Causes of Drought. Under the auspices of the U.S. Climate Variability and Predictability (CLIVAR) project, a number of CCSP agencies initiated an activity in FY 2007 to support research into the physical and dynamical mechanisms leading to drought and the mechanisms through which drought may change as climate changes. The Drought in Coupled Models Project (DRICOMP) focuses on evaluating a variety of existing model products to address issues like the roles of the oceans and the seasonal cycle in drought, the impacts of drought on water availability, and distinctions between drought and drying. Based on a competition during FY 2007, 16 projects were selected to analyze and evaluate unforced control runs archived as part of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project 3 (CMIP3) multi-model data set, as well as the multi-model simulations of 20th-century climate and the long stabilized simulations with forcing held fixed at future climate conditions. The objective of DRICOMP is to increase community-wide diagnostic research into the physical mechanisms of drought and to evaluate its simulation in current models. DRICOMP will lead to more robust evaluations of model projections of drought risk and severity and thus to a better quantification of the uncertainty in such projections. In FY 2009, a workshop will be held during which results of the DRICOMP project will be summarized, and results from this interagency-supported project will be published.

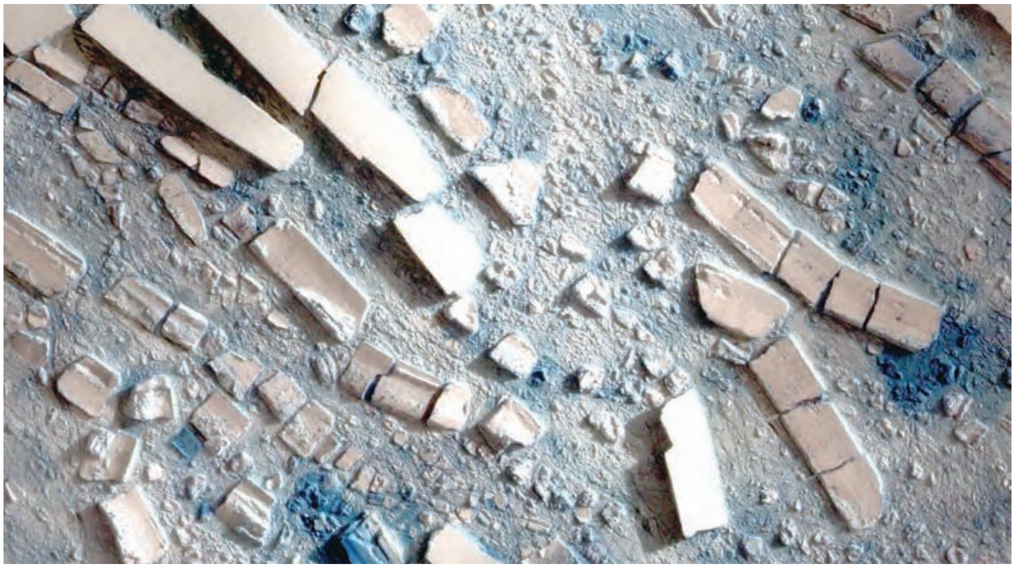
This activity will address Goals 1 and 3
and Questions 4.2, 4.3, and 4.5 of the CCSP Strategic Plan.



Abrupt Climate Change and the Atlantic Meridional Overturning Circulation. The AMOC is thought to play an important role in the global ocean circulation, and therefore consequences to climate resulting from its variability, particularly in the North Atlantic, could be significant. Despite the potential for serious impacts, there are substantial gaps in knowledge concerning the AMOC and how it varies within the global climate system. Responding to recommendations in the report *Charting the Course for Ocean Science in the United States for the Next Decade:*

An Ocean Research Priorities Plan and Implementation Strategy by the National Science and Technology Council Joint Subcommittee on Ocean Science and Technology, several CCSP agencies will implement a program in FY 2009 that will lead to new capabilities for monitoring and predicting AMOC changes. In addition, it is anticipated that an abrupt climate change modeling activity initiated in FY 2008 will be continued in FY 2009. This activity would focus on examining attribution of past abrupt climate change, as well as the likelihood of future abrupt climate change based on climate change projections using dynamical coupled climate models.

This activity will address Goals 1 and 3 and Questions 4.1, 4.2, 4.3, and 4.5 of the CCSP Strategic Plan.



Improving High-End Modeling Capabilities for Decision Support. Modeling efforts will emphasize the continuing development of global and regional high-resolution atmospheric models. One major emphasis is to improve simulations of the climatology, interannual variability, and trends in Atlantic hurricane activity. These dynamical modeling studies promise to provide essential information to complement observational research based on historical hurricane records. In addition, through the North American Regional Climate Change Assessment Program (NARCCAP), several regional models will be used to downscale global model projections used in the IPCC Fourth Assessment Report to better estimate future climate changes over North America. NARCCAP modeling efforts will be complemented by global atmospheric model runs at high resolution (~50 km) over specific time periods performed at the Geophysical Fluid Dynamics Laboratory and the National Center for Atmospheric Research.

This activity will address CCSP Goal 3 and Questions 4.1, 4.2, 4.4, and 4.5 of the CCSP Strategic Plan.

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