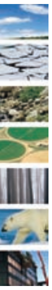


2 | Climate Variability and Change

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.

Recognizing that the climate system operates seamlessly across time scales, CCSP-supported research encompasses both short-term climate variability and longer term climate change. The connection between higher frequency fluctuations and climate change is the focus of several recent studies on potential relationships between hurricane activity and long-term increases in tropical sea surface temperatures (see discussion in Analysis of Progress Toward Goals section). Interactions among climate system components—for example, involving the atmosphere, oceans, land surface, and cryosphere—are also of fundamental importance to understanding past and projecting future climate changes. Such interactions are vital in explaining past abrupt climate changes, which paleoclimatic evidence suggests have occurred in periods as short as years to decades.[1] An important goal of CCSP research is to assess the likelihood of future abrupt climate changes and to identify the requirements for an early warning system to detect and predict such changes.

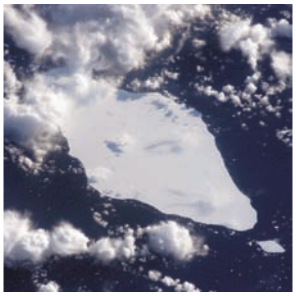
Identifying links and feedbacks among climate system components poses challenges in designing observing systems to monitor the climate system adequately and in constructing models that can properly reproduce past, and confidently project future, climate system behavior. Toward this end, a new generation of climate models that incorporates improved representations of physical processes, increased resolution, and coupling of the different climate system components is being developed within an Earth system modeling framework. Such Earth system models, in combination with global Earth observations, are essential to produce internally consistent maps of atmospheric, oceanic, land surface, and ice conditions, called "Earth system analyses," both in near real-time and retrospectively. The development of such analyses will provide decisionmakers with new tools to visualize the evolving state of the full climate system over the entire planet and provide researchers with the ability to better explain observed changes.

Research within the Climate Variability and Change (CVC) element focuses on two broad, critically important questions to society as defined in the *CCSP Strategic Plan*:

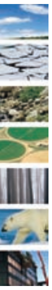
- How are climate variables that are important to human and natural systems affected by changes in the Earth system resulting from natural processes and human activities?
- How can emerging scientific findings on climate variability and change be further developed and communicated in order to better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



CVC research encompasses activities spanning the reconstruction of the climate before the era of modern observing systems (paleoclimate) through model-based projections of future climate change. This section begins with highlights from paleoclimate research published within the past year. Paleoclimate research has proven invaluable in identifying the rates and magnitudes of past climate changes, determining mechanisms that can produce such changes, and helping to constrain estimates of climate system sensitivity in response to changes in radiative forcing. Paleoclimate studies also enable evaluations of climate model performance over far longer time periods and ranges of forcing than would be possible from only modern observational records.



The Pliocene Paradox.[2] During the early Pliocene 3 to 5 million years ago, the intensity of sunlight incident on Earth, the global geography, and the atmospheric concentration of carbon dioxide were similar to today's values, but surface temperatures in polar regions were much higher than today. Continental glaciers were absent from the Northern Hemisphere, and sea level was 25 m higher than at present. This paradox—that the early Pliocene climate was much warmer than today despite similar external forcing—has potential implications for climate stability. It raises the possibility that future melting of glaciers, changes in the hydrological cycle, and a deepening of the upper mixed layer of the ocean could lead to a return toward much warmer conditions similar to the early Pliocene.

Paleoclimate Evidence for Future Ice-Sheet Instability.[3] Conditions during the last interglacial period (129,000-118,000 years ago) as deduced from coral records provide evidence that sea level during this epoch was from 4 to over 6 m above present levels. If current trends in polar warming continue over the next century, climate conditions similar to those of the last interglacial period may result in Arctic and Antarctic ice melt, with sea level rising well beyond current estimates.

High-Resolution Paleoclimate Records.[4] Research on marine fossils suggests that waters in the central Gulf of California were especially warm during the Medieval Warm Period from approximately AD 900 to1160. A present-day relationship exists between warmer sea surface temperatures in the northern Gulf and more intense development of the North American monsoon in Arizona and New Mexico. Increased monsoonal rainfall during the Medieval Warm Period has also been found in Florida and the Indian Ocean. Increased solar radiance is considered as a possible forcing mechanism.

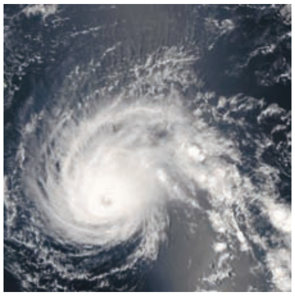
Reconstructions of Streamflow in the Upper Colorado and South Platte River Basins.[5] Measurements from moisture-sensitive trees in Colorado have been used to extend streamflow records in the Upper Colorado and South Platte River basins back 300 to 600 years, significantly augmenting river gage records. The results indicate that the 20th-century climate is not representative of the range of hydrological extremes due to natural climate variability. For example, multi-year drought events more severe than the 1950s drought occurred as recently as the 19th century. Water managers are now using the paleo-streamflow reconstructions to better

estimate the potential range of natural hydroclimatic variability in the Upper Colorado and South Platte River basins.

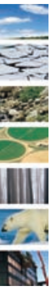
Estimated Climate Sensitivity Constrained by Temperature Reconstructions over the Past Seven Centuries.[6] Climate sensitivity, defined as the equilibrium response of global mean surface temperature to a doubling of carbon dioxide, is an important indicator of the potential for future global warming. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report gives a 5 to 95% range of climate sensitivity of 2 to 4.5°C, with a most probable value of 3.0°C. Some studies suggest, however, the possibility of much higher sensitivities, at or above 8°C. A recent study examines the plausibility of such high sensitivities by using an energy balance model forced by solar, volcanic, and greenhouse gases. This model is used to simulate paleoclimate reconstructions of Northern Hemisphere temperatures over the past 7 centuries. The method involves determining the climate sensitivities that yield simulations in best agreement with proxy reconstructions. After accounting for the uncertainties in temperature reconstructions and estimates of past external forcing, the analysis suggests that the most likely range of climate sensitivity is 1.5 to 6.2°C, and that higher climate sensitivities are inconsistent with paleoclimate evidence.

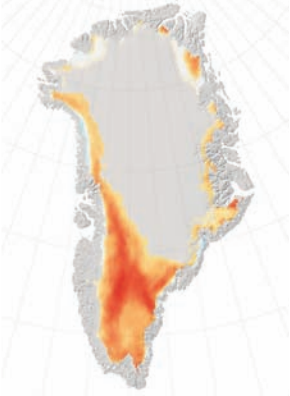
Studies within the era of modern climate observations are helping to illuminate interactions among climate system components, as well as the connections between longer term climate changes and short-term weather and climate phenomena, including extreme events like hurricanes.

Climate Variability and Change and Hurricanes.[7,8,9,10,11,12,13] There is observational evidence of an increase in intense hurricane activity over the North Atlantic Ocean since around 1970 that is correlated with increasing tropical Atlantic sea surface temperatures. Climate model simulations indicate that sea surface temperature changes in the Atlantic and Pacific tropical cyclone development regions during the 20th century have significant contributions from anthropogenic forcing as well as natural variability. Evidence for changes in tropical cyclone activity outside the Atlantic is mixed, however, with results varying with the ocean basin, period of record, data set, and analysis technique. Because of these and other issues, the reliability



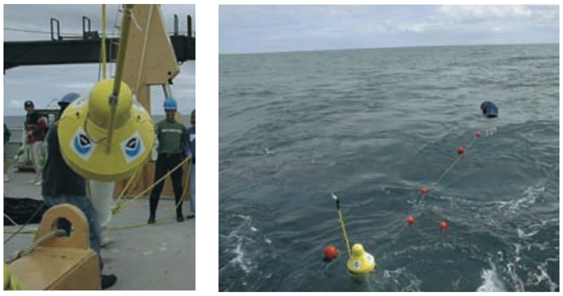
of existing data sets for tropical cyclone trend detection has been questioned. There is general agreement on the need for further work to improve the quality of historical tropical cyclone data sets.



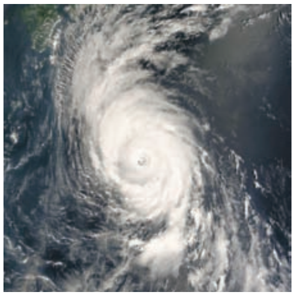


Advances in Detecting Ice Sheet Changes.[14,15,16] Studies applying sensitive gravimetric measurements show net decreases over recent years in the mass of the Greenland and Antarctic Ice Sheets. These reductions appear to be due to increased melting around the ice margins and widespread acceleration in the seaward flow of outlet glaciers. Because of the implications for the rate of sea-level rise, key challenges for future research are to refine further the accuracy of direct observations of ice sheet changes and to improve understanding and modeling of the processes contributing to these changes.

Interannual and Decadal Variability in Ocean Heat Content.[17,18,19] The global ocean has approximately one thousand times the heat capacity of the atmosphere, so monitoring ocean heat content is of fundamental importance to detect and understand changes in the Earth's heat balance. While observations show a general increase in the global ocean heat content over the past half-century, amounting to over 80% of the total heat gain of the climate system, there is large uncertainty due to deficiencies in the historical record of ocean temperature in the Southern Hemisphere. Moreover, the decadal signals are complicated by substantial multi-year fluctuations caused by volcanic activity and/or short-term climate variations such as El Niño. For the recent decade 1993 to 2003, when spatial coverage of measurements improved, enhanced ocean warming accounts for about one-half of global sea-level rise, due to thermal expansion of seawater. Global coverage from 60°S to 60°N of upper ocean temperature was achieved in 2004 by the Argo float project, and Argo data indicate that ocean heat content was approximately constant for the period 2004 to 2006. A significant challenge for understanding the climate system is to correctly represent the interannual to decadal variability of ocean heat content in ocean models.



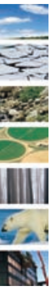
Vegetation-Climate Feedback.[20,21] Understanding the present-day relationships between climate and the ranges of plant species is key to both interpret past changes in plant distributions and to assess the effects of potential future climatic changes on ecosystems. CCSP researchers are conducting analyses that provide direct comparisons of the geographic distributions of temperature, moisture, and bioclimatic parameters with the ranges of ecoregions and key plant species in North America. Two new volumes of the *Atlas of Relations between Climatic Parameters and Distributions of Important Trees and Shrubs in North America* explore the influence of climate on woody species and ecoregions in Alaska and on ecoregions of North America as defined by three different approaches. The data presented in these volumes are being employed to interpret the climatic changes associated with geologic records of ecosystem changes over the past 20,000 years in North America. These data also provide the basis for modeling potential changes in ecosystems that would occur under a range of future climate change scenarios.



North American Monsoon Data Analysis and Modeling.[22,23,24] Data collected during the North American Monsoon Experiment (NAME 2004) were used in global and regional data analysis and forecast experiments at the NOAA National Centers for Environmental Prediction (NCEP) to test their impact on operational climate products. The NAME 2004-enhanced soundings appear to have a significant beneficial influence on NCEP's operational analyses, particularly over the core monsoon area and in regions where uncertainties are largest. Analyses from the NAME Model Assessment Project show that current models are capable of simulating the general evolution of a summer precipitation maximum near the core monsoon region. Important differences in the monthly evolution and diurnal cycle of precipitation generated by the models were also found, including significant delays of up to a full month in monsoon onset compared to observations. A special issue of *Journal of Climate* published in 2007 includes 22 papers on scientific progress resulting from NAME 2004.

Ozone Increases in the Antarctic Middle Stratosphere.[25,26] An increase in summer ozone concentrations in the Antarctic middle stratosphere has been seen in satellite measurements over the last 2 decades, and its general characteristics have been replicated in a computer model that includes interactive coupling of chemical and meteorological processes. The model yields a summer increase because of changes in polar stratospheric winds that are forced by radiative perturbations associated with the much larger ozone decreases in the lower Antarctic stratosphere. The model findings provide an important evaluation of coupled chemistry-climate models and increase confidence in our ability to make future projections. Other modeling research has shown that warming of the tropical troposphere due to increased greenhouse gases may accelerate the circulation of the stratosphere and thus alter the global distribution of ozone.

Pollution Darkened China's Skies.[27] Records from more than 500 weather stations across China for the years 1954 to 2001 indicate China has darkened over the past half-century. On the other hand, in the most comprehensive study to date of overcast



versus cloud-free days in China, researchers have found that cloud cover has been decreasing for the past 50 years. Less cloud cover, regardless of its cause, should have resulted in more solar radiation reaching the surface. Surprisingly, though, the data show that both solar radiation and pan evaporation decreased in most parts of China by 1.9% (3.1 Wm^{-2}) and 2.2% (39 mm) per decade, respectively. Combined with evidence from other studies of decreased sunshine duration, reduced visibility or clearness, and elevated aerosol optical depth, it appears that air pollution produced a fog-like haze, which reflected and absorbed radiation from the sun and resulted in less solar radiation reaching the surface, despite concurrent upward trends in cloud-free skies over China.

CVC research also encompasses the development and application of climate models of varying complexity. These models are used to understand past climate variations, help explain causes of current climate conditions, and improve short-term climate predictions as well as projections of future climate change.

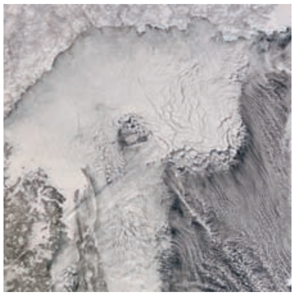
Mountain Snowpack Projected to Decline.[28] A global climate model with an embedded downscaling scheme predicts that regional mountain snowpack will decline by up to 50 to 80% in many regions of the globe over the next century in response to a scenario of increasing greenhouse gas concentrations in the atmosphere. Previous studies with regional climate models have suggested similar reductions for selected regions and decades in the 21st century. Now, for the first time, a global climate model provides global estimates of snowmelt with 5-km spatial resolution for the period 1980 to 2100. To achieve this resolution, a physically based downscaling scheme was added to the Community Climate System Model (CCSM) that is fully interactive with the atmosphere and land components of the CCSM. Snowpack is most sensitive to spatial resolution because of its dependence on both temperature and precipitation, both of which also depend on surface elevation.

Reducing Uncertainties in Projections of the Thermohaline Circulation.[29] The ocean thermohaline circulation (THC) plays an important role in Earth's climate by transporting heat from low latitudes. Changes in the THC and, in particular, a shutdown of this circulation due to large freshwater input at high latitudes, have been identified as a likely candidate for explaining some past rapid climate changes. A recent study applied a suite of climate models to examine how the THC may respond to additions of freshwater in the North Atlantic Ocean that could accompany future climate change. In response to expected levels of freshwater input, the models yield generally similar amounts of THC weakening over the next 100 years, on the order of 30% on average, and none of the models simulated a complete shutdown during this period.

Identifying Robust Responses to Anthropogenic Climate Forcing.[30,31] Analyses of climate model simulations generated for the IPCC Fourth Assessment Report have identified several highly reproducible hydrological and atmospheric circulation responses to past and projected future climate forcing. Examples of these robust responses include strong subtropical drying; weakening of large-scale tropical circulations, including an east-west wind pattern over the tropical Pacific known as the Walker circulation; and a poleward expansion of a north-south tropical wind pattern known as the Hadley circulation. A study of the hydrological cycle response shows that, contrary to conventional wisdom, nearly all of the models generate positive cloud feedback, indicating that in these models changes in clouds are amplifying the amount of global warming.

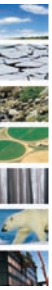
IPCC Model Analyses and Evaluation.[32,33,34,35,36,37,38] Substantial efforts were devoted to develop and analyze the model runs for the IPCC Fourth Assessment Report. Numerous publications describing the National Center for Atmospheric Research CCSM, the NOAA Geophysical Fluid Dynamics Laboratory CM2, and the NASA Goddard Institute for Space Studies EH models are now available. All models are consistent in projecting global warming in the 21st century in response to anthropogenic forcing. The models also include improved El Niño Southern Oscillation (ENSO) characteristics but still have trouble depicting many aspects of ENSO variability and its effects on climate in North America and elsewhere. Generally, only a few models are able to successfully replicate monsoon precipitation patterns. These deficiencies represent fundamental challenges that will need to be addressed in future climate models.

Highlights of Plans for FY 2008



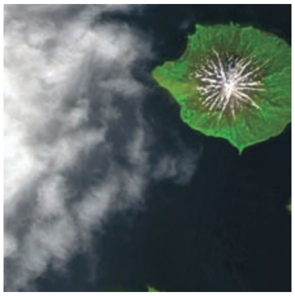
Development of a Permafrost Monitoring Network. Climate projections by coupled atmosphere-ocean global circulation models suggest significant environmental changes will occur in the Arctic during the next 80 years. Given the large potential impacts, and the significant uncertainty in the model projections, the U.S. Department of the Interior is developing a long-term permafrost monitoring network on Federal lands in northern Alaska; this network contributes to the Global Terrestrial Network for Permafrost and the Global Climate Observing System. Analysis of data acquired thus far by the monitoring network suggests that permafrost temperatures on the western half of the Arctic Coastal Plain in Alaska may have warmed several degrees Celsius between 1980 and 2005.

This activity will address Goals 1 and 4 and
Questions 4.3 and 4.5 of the CCSP Strategic Plan.



Yukon River Basin: An Arctic Benchmark. A developing consortium of U.S. and Canadian Federal, state, and provincial agencies, university scientists, and tribal organizations is initiating a major campaign to understand and predict climate-induced changes to the air, water, land, and biota within the Yukon River Basin (YRB). The consortium will implement a prototype environmental monitoring and research strategy that links air, water, soil, and forest information to understand changes in carbon and energy budgets across the Arctic, boreal, and Arctic Ocean systems. This collaborative scientific campaign, using the YRB and adjacent coastal ocean as a representative landscape unit, will provide a benchmark for tracking and understanding changes occurring throughout the Arctic and subarctic region.

This activity will address Goals 1, 2, and 4 and
Questions 4.3, 4.4, 6.4, and 7.1 of the CCSP Strategic Plan.



Field Experiment to Improve Understanding of Southeast Pacific Climate Processes. The Variability of the American Monsoon System (VAMOS) Ocean-Cloud-Atmosphere-Land Study - Regional Experiment (VOCALS-REx) is planned for October and November 2008. This international field experiment is designed to better understand physical and chemical processes central to the climate system of the Southeast Pacific (SEP) region. The climate system of the SEP involves tightly coupled, but poorly understood, interactions among the ocean, atmosphere, and land. VOCALS-REx will focus on interactions among clouds, aerosols, marine boundary layer processes, upper ocean dynamics and thermodynamics, coastal currents and upwelling, large-scale subsidence, and regional diurnal circulations to the west of the Andes mountain range (see Figure 3). Multidisciplinary intensive observational data sets will be obtained during VOCALS-REx from several platforms including aircraft, research vessels, and a surface land site. An intensive observational period will take place during October and November, when the extent of stratocumulus over the SEP is at its greatest, the southeast trade winds are at their strongest, and the coupling between the upper ocean and the lower atmosphere is at its tightest.

This activity will address Goals 1 and 2 and
Questions 3.1 and 4.2 of the CCSP Strategic Plan.

Constructing a Satellite-Era Reanalysis of the Coupled Ocean-Atmosphere System. A national capacity for integrated Earth system analysis is being developed that extends beyond current attempts to map individual components of the Earth system separately. Achieving this capability requires parallel advancements in coupled Earth system

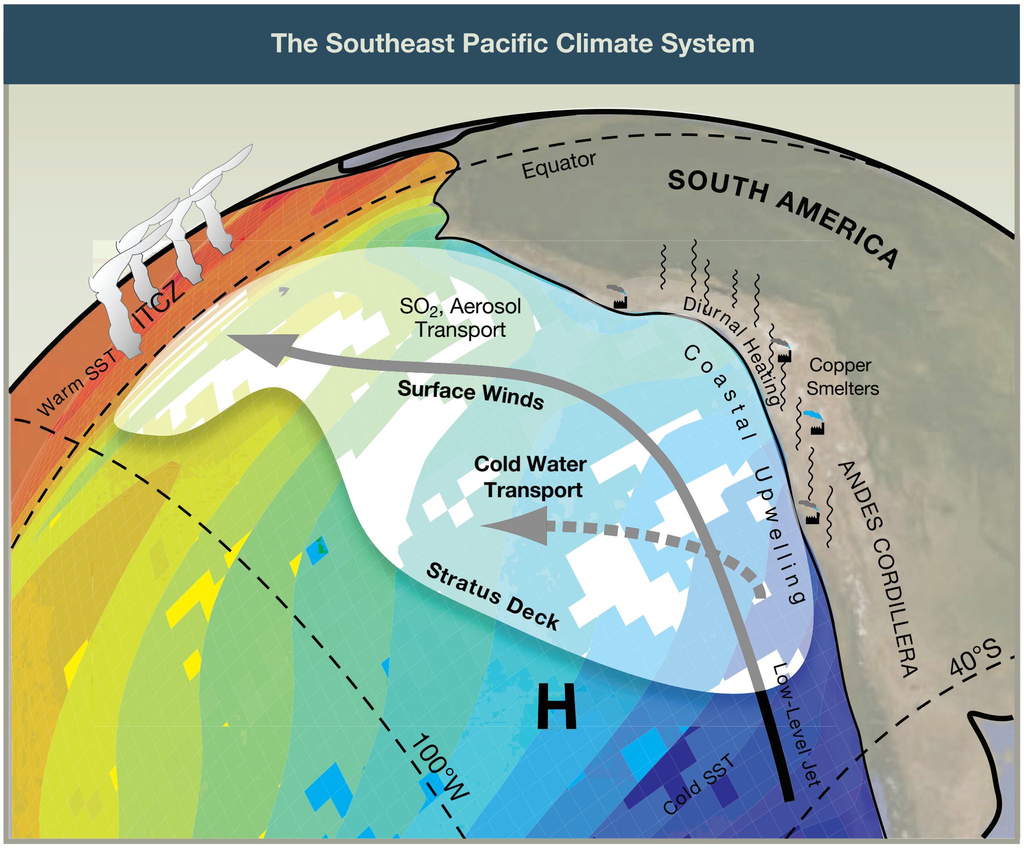
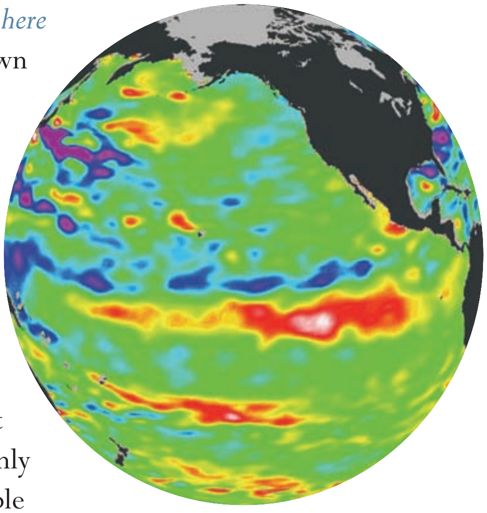

The Southeast Pacific Climate System

Figure 3: The Southeast Pacific Climate System. Schematic view of the coupled ocean-atmosphere-land system in the vicinity of the southeast Pacific. The interactions among clouds, aerosols, coastal upwelling and currents, upper ocean dynamics, and regional circulations influenced by the Andes are poorly understood and not well modeled, and yet these interactions over the southeast Pacific affect regional and global climate. Surface winds, faced with the Andes barrier, flow parallel to the coast and bring deep, nutrient-rich waters to the surface. These cold waters, aided by an air mass made stable in part by effects of the Andes, help support the largest and most persistent subtropical sheet of stratus and stratocumulus clouds on the planet. This cloud deck, affected by aerosols from both natural and human sources, helps in turn to maintain cool ocean waters beneath. A field campaign, VOCALS, is planned in 2008 to obtain measurements to better understand this complex system and to provide a basis for model improvements. *Credit: R. Wood, University of Washington.*

modeling, and considerable progress is being made in this latter arena, particularly with the adoption by the research and operational forecasting communities of a common Earth system modeling framework. A coupled ocean-atmosphere model is currently in operational use, and during 2008 this model will serve as the basis for beginning the first attempt to create a reanalysis of the coupled ocean-atmosphere system dating back to the start of the satellite era (1979) through 2007. Development of a coupled ocean-atmosphere analysis capability will also support intensified efforts to improve the monitoring and understanding of changes in the ocean thermohaline circulation.

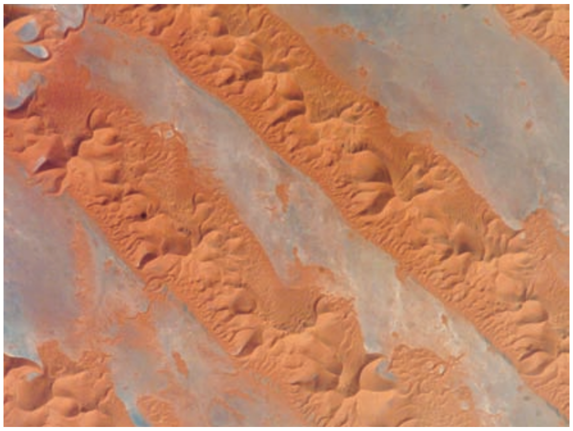
This activity will address Goals 1 and 3 and
Questions 4.2, 4.4, and 4.5 of the CCSP Strategic Plan.



Creating a Historical Reanalysis of the Atmosphere of the 20th Century. Recent research has shown the feasibility of using modern data assimilation techniques together with observations of sea-level pressure to produce, for the first time, a global analysis of tropospheric weather patterns at 6-hour temporal resolution that extends over the entire 20th century. Production of this historical reanalysis will be initiated in 2008, with the goal of at least doubling the length of current reanalysis records, which now extend back only until 1948. This historical reanalysis will enable researchers to address such questions as 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. A century-long 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.

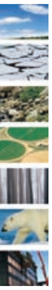
This activity will address Goals 1 and 3 and
Questions 4.2, 4.4, and 4.5 of the CCSP Strategic Plan.

Drought in Coupled Models Project. A new, multi-agency activity will support research into the physical and dynamical mechanisms of drought and the mechanisms through which drought may change as climate changes. Relevant issues include the role of the



seasonal cycle in drought, the impacts of drought on water supplies, and the distinction between drought as a transient phenomena and drying produced by long-term changes in a region's water balance. A broad range of model simulations will be analyzed and evaluated in this effort, including multi-model simulations of 20th-century climate, model projections of future climate, paleoclimate simulations of the last glacial maximum, and seasonal model prediction data sets. The objective is to increase community-wide diagnostic research into the physical mechanisms of drought and to evaluate drought simulations by current models. This effort will lead to more robust evaluations of model projections of drought risk and severity, and to a better quantification of the uncertainty in such projections.

This activity will address Goals 1 and 3 and Questions 4.1, 4.2, 4.4, and 5.1 of the CCSP Strategic Plan.



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