3 | Global Water Cycle

Strategic Research Questions

5.1 What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

5.2 How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

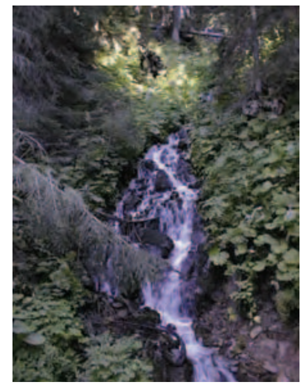
5.3 What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

5.4 What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

5.5 How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

See Chapter 5 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

The global water cycle plays a critical role in the functioning of the Earth system. Through complex interactions, the global water cycle integrates the physical, chemical, and biological processes that sustain ecosystems and influence climate and related global change. Inadequate understanding of the water cycle is one of the key sources of uncertainty in climate prediction. Clouds, precipitation, and water vapor produce feedbacks that alter surface and atmospheric heating and cooling rates, leading to adjustments in atmospheric circulation and precipitation patterns – processes current climate models do not adequately represent. Improved understanding of these processes will be essential to developing options for responding to the consequences of water cycle variability and change. For these reasons, water cycle research is a high-priority area for near-term activities within CCSP.



Priorities in FY 2006 include the planning of integrated projects to aggressively accomplish the *CCSP Strategic Plan* goals for water cycle research. As part of this process, the CCSP participating agencies involved in the global water cycle research element are defining a program of activities that will produce the kinds of interdisciplinary breakthroughs the water cycle science community has identified as essential. These activities are organized around the need for comprehensive coincident measurements of all aspects of the water cycle, including atmospheric, surface, and subsurface observations. Observational data sets that capture key features of the water cycle at the same place and time promise to improve estimates of key fluxes and stores within the linked water and energy cycles, which are needed to balance water and energy budgets. In addition, long-term records of water cycle variables are vital for assessing changes in the Earth system. Implementation planning includes strategies for assembling long-term data sets of water cycle variables, including new tools and techniques, reanalysis of existing records, assimilation of observations and model output, and establishment of a network of observation stations with new capabilities for collecting and integrating data for interdisciplinary research. In addition to addressing CCSP goals, these ongoing and planned observations will support the objectives of the Global Earth Observing System of Systems (GEOSS).

The global water cycle research element is continuing to pursue a set of important, long-term priorities. For example, insights into the formation and behavior of clouds and precipitation, including better characterizations of the phase changes of water in clouds and the phases and onset of precipitation, are emerging from field campaigns and model studies and will be promoted in continuing activities of the global water cycle research element. Similarly, the predictability of regional precipitation will be assessed and better understood by ongoing diagnostic and modeling studies that identify the connections between regional- and global-scale phenomena, land-surface conditions (such as soil wetness), and rainstorms. Results from these studies show promise of leading to earlier (and more accurate) predictions and improved ability to assess hazards and risks of extremes such as floods and droughts, as well as more efficient water resource management. In this context, the results of advances in coupled ocean-atmosphere-land models will be important.

The ultimate goal of this water cycle research is to provide a better foundation for decisions and investments by policymakers, managers, and individuals. Achieving this goal requires a program of activities that test predictions and data products in real decision contexts, demonstrate techniques and their effectiveness to potential users, and provide tools and strategies to transfer the science from the experimental realm to operations. Implementation of the *CCSP Strategic Plan's* global water cycle research strategy addresses these issues.

Highlights of Recent Research

Selected highlights of recent research supported by CCSP participating agencies follow. These research results address the strategic research questions on the global water cycle identified in the *CCSP Strategic Plan*.

Variations of U.S. Drought Occurrence Related to Fluctuations in Sea Surface Temperatures in the North Atlantic.[11] Researchers analyzed precipitation data to identify spatial and temporal variation of drought occurrence in the conterminous United States during the 20^{th} century. They found that these variations were largely (74%) explained by multi-decadal fluctuations in sea surface temperatures in the North Atlantic and North Pacific Oceans and by the long-term trend in Northern Hemisphere temperatures. The results suggest that persistence of the present warm conditions in the North Atlantic into the next decade may lead to continuation of the present western drought pattern, which is similar to that of the 1950s, or to development of a drought pattern similar to that of the 1930s.

North American Climate: Water Cycle and the Pacific Decadal Oscillation.[2] Two main characteristics distinguish the Pacific Decadal Oscillation (PDO) from the El Niño Southern Oscillation (ENSO). First, 20^{th} century PDO "events" persisted for 20 to 30 years, while typical ENSO events persisted for 6 to 18 months. Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics – but the opposite is true for ENSO. Major changes in northeast Pacific marine ecosystems have been correlated with phase changes in the PDO. Even in the absence of a full theoretical understanding of the PDO, information about its phase can improve season-to-season and year-to-year climate forecasts for North America because of its strong tendency for multi-season and multi-year persistence. For the past several years, North Pacific sea surface temperature variations have not consistently correlated with either the warm or cool phases of the PDO pattern (see top panel of Figure 9). The PDO index has been highly variable. The 1900 to 2004 time series of the PDO index is shown in the bottom panel of Figure 9. Monthly updates of the PDO index are available at <jisao.washington.edu/pdo/PDO.latest>.

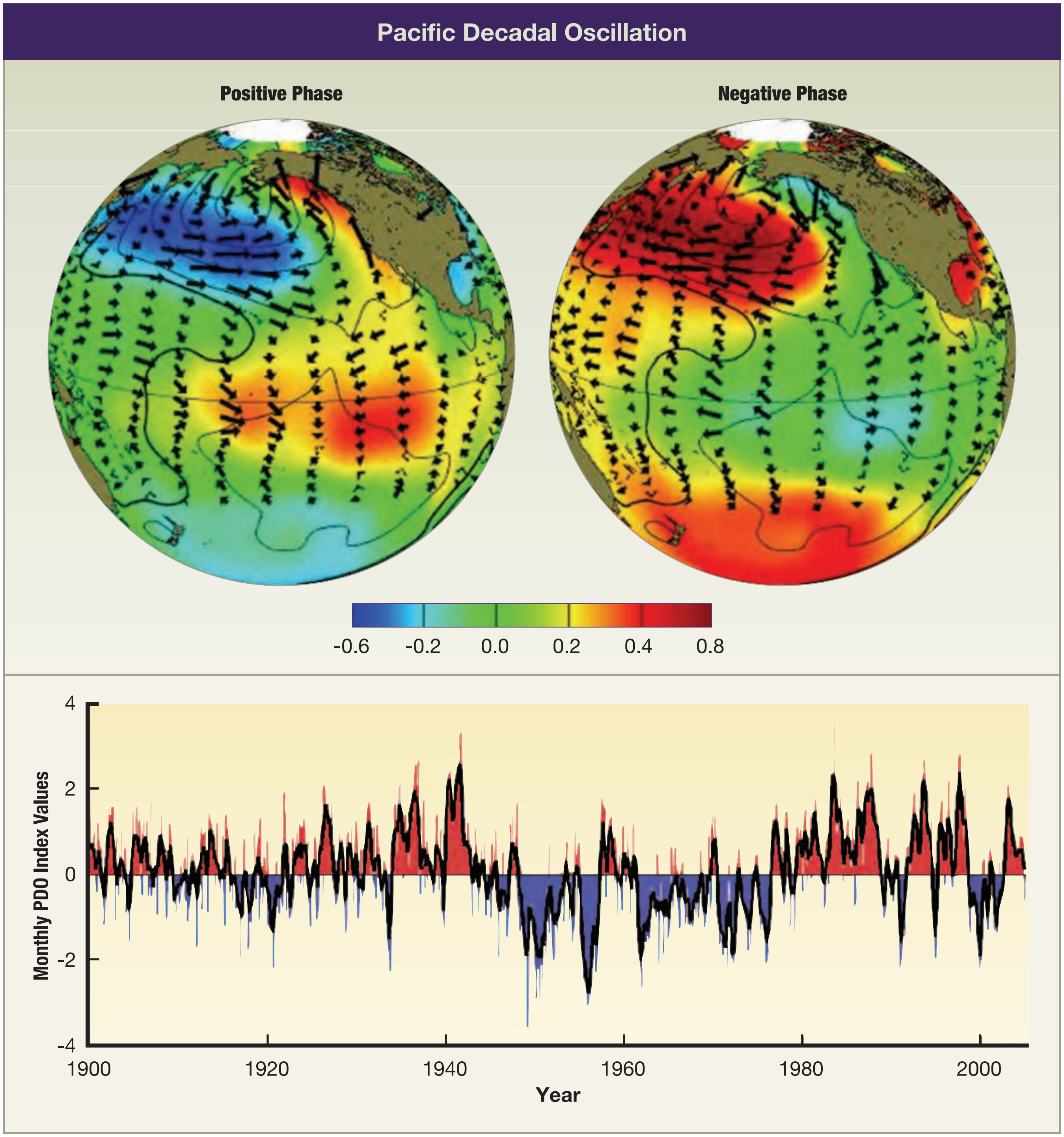


Figure 9: Pacific Decadal Oscillation.(top) Typical wintertime sea surface temperature (colors), sea level pressure (contours), and surface wind stress (arrows) anomaly patterns during positive and negative phases of the Pacific Decadal Oscillation (PDO), as derived from the TOPEX/Poseidon satellite plus other ocean/atmosphere data. Temperature anomalies (colors) are in degrees Celsius. (bottom) Monthly values for the PDO index, 1900-2004. *Credit: S. Hare and N. Mantua, University of Washington.*

Observed and Projected Changes in U.S. Snowpack and Runoff.[3,4,6,7,9,14,15] Observations from the past 5 decades indicate that the spring snowpack in the Pacific Northwest has declined significantly since the mid-20th century. At most of the mountain locations studied, declines in snow water equivalent (the depth of liquid water from the melted snow) coincide with significant increases in temperature, and have occurred despite increases in precipitation. The largest decreases have occurred at the lowest elevations, suggesting that moderate warming throughout the region may have raised the elevation of freezing level. These snowpack declines have been accompanied by an earlier annual peak in river runoff. Researchers have found that, across several hundred stream gages in mountainous western North America from New Mexico to Alaska, as well as New England, the snowmelt runoff season has come earlier in recent decades, with average timing shifts (by several measures) of 1 to 2 weeks earlier. These long-term timing shifts have been most strongly related to changes in seasonal temperatures during the snowmelt runoff season, and have not been significantly related to winter and spring precipitation. These results have significant implications for water resource managers since snowmelt provides much of the water used during summer for irrigation, energy production, municipal and industrial water supply, fish and river ecosystem protection, recreation, and other uses.

Additional studies have addressed possible implications of potential future greenhouse gas-induced climate change on the mountain snowpack and runoff in the western United States. These studies used the Intergovernmental Panel on Climate Change (IPCC) business-as-usual greenhouse gas emission scenario to drive multiple simulations of the Parallel Climate Model (PCM). In one study, annual snowpack was projected to be 20 to 70% smaller by the middle of the 21st century when the PCM output was downscaled (i.e., translated from coarse to fine resolution) with the MM5 regional climate model. Somewhat smaller snowpack reductions were found when the downscaling was performed using the Regional Spectral Model. Using the same PCM simulations, other studies suggest that reservoir levels may decline by approximately one-third in the Colorado River Basin by the end of the 21st century and that streamflow timing in most western North American streams might be roughly a full month earlier. However, there is significant uncertainty associated with downscaling climate projections to fine resolutions. Moreover, different results may be obtained if other global climate models or forcing scenarios are used. For example, the PCM projects less warming from greenhouse gas increases than most other climate models.

Projections of Global-Scale Runoff and Soil Moisture Changes.[10] Scientists have also examined the potential for significant global-scale changes in river discharges and soil wetness over the rest of the 21st century due to greenhouse warming. Their analysis of model projections, based on a typical greenhouse gas emission scenario, indicates that the discharges from Arctic rivers such as the Mackenzie may increase by up to 20% (of the pre-Industrial Period level) by the middle of the 21st century and by up to 40% or more in a few centuries. In the tropics, the discharges from the Amazon and Ganga-Brahmaputra rivers are also projected to increase substantially. However, the projected changes in runoff from other tropical and many mid-latitude rivers are smaller (on a percentage basis), with both positive and negative signs. For soil moisture, the results of this study indicate reductions during much of the year in many semi-arid regions of the world, such as southwestern North America, northeastern China, the Mediterranean coast of Europe, and the grasslands of Australia and Africa. The projected reduction is particularly large during the dry season (on a percentage basis). From middle to high latitudes of the Northern Hemisphere, this study projects soil moisture to generally decrease during the summer growing season but increase in winter.

North American Monsoon Experiment Field Campaign. Most summer precipitation around the world is driven by strong solar heating of the land surface. The consequent large summer land-ocean temperature contrasts lead to summer monsoon circulations typically characterized by a systematic reversal of wind patterns and very strong rainfall events. The North American summer monsoon is one major component of the world's monsoon systems, the others being the Asian-Australian monsoon and the African monsoon systems. These systems interact with the El Niño/La Niña cycles, among others. The North American Monsoon Experiment (NAME) field campaign was conducted in, over, and around the southwestern United States and northern Mexico during the summer of 2004 and involved internationally coordinated research (see <www.cpc.ncep.noaa.gov/products/precip/monsoon/NAME.html>). NAME aims at determining the sources and limits of predictability of summer precipitation from the monsoon over North America. The field campaign was motivated by previous and ongoing diagnostic and modeling studies, which identified processes contributing to the variability of monsoonal circulation, convection, and precipitation. The field experiment significantly enhanced the spatial and temporal resolution of observations of those processes available for the monsoon region. The results of NAME, currently being analyzed, will be used to attempt to improve warm-season weather predictions in 2006 and beyond.

Madden-Julian Oscillation and Floods.[1] Recent studies have revealed relationships between the Madden-Julian Oscillation (MJO) and precipitation that may provide an important key to prediction of flooding over southwest Asia. The MJO (also referred to as the 30-60 day or 40-50 day oscillation) is thought to be one of the main intra-seasonal fluctuations that explain weather variations in the tropics. The MJO is associated with variations in surface and upper-level wind fields, sea surface temperature, and cloudiness/rainfall. It affects the entire tropical troposphere, but is most evident in the Indian and western Pacific oceans with an active (wet) phase and an inactive (dry) phase. The MJO is strongest in the eastern Indian Ocean, when its wind anomalies extend over southwest Asia. A 22-year record of precipitation observations over southwest Asia shows that there is a 55% increase in daily precipitation when the MJO is in its active phase. The effect of the MJO is quite consistent from year to year, with more rain attributed to the MJO as it circumnavigates the globe in each of the 22 years in the record. These findings indicate that the evolutions of storms over southwest Asia and resultant precipitation could conceivably be forecast with some skill for 3-week periods.

Glacier Mass-Balance Records Show a Retreating Trend in Alaska Glaciers.[5] CCSP-supported scientists continue to monitor long-term glacier mass balance at three benchmark glaciers in Washington and Alaska, each in a different climate regime. Winter accumulation, summer ablation, and net mass balance are measured using accepted glaciological techniques. The data collected are posted on the Internet (see <ak.water.usgs.gov/glaciology>). The mass balance records extend for 50 years at South Cascade Glacier, Washington, and 38 years at Gulkana and Wolverine Glaciers, both in Alaska. These records are among the longest in North America. The data are used to understand glacier-related hydrologic processes and to improve the quantitative prediction of water resources, glacier-related hazards, and the consequences of climate change. Consistent with the observed warming, for the past quarter century these glaciers have experienced almost continuous negative net balances, indicative of the glacier retreat observed in the glaciated regions of the Pacific Northwest and Alaska (see Figure 10).

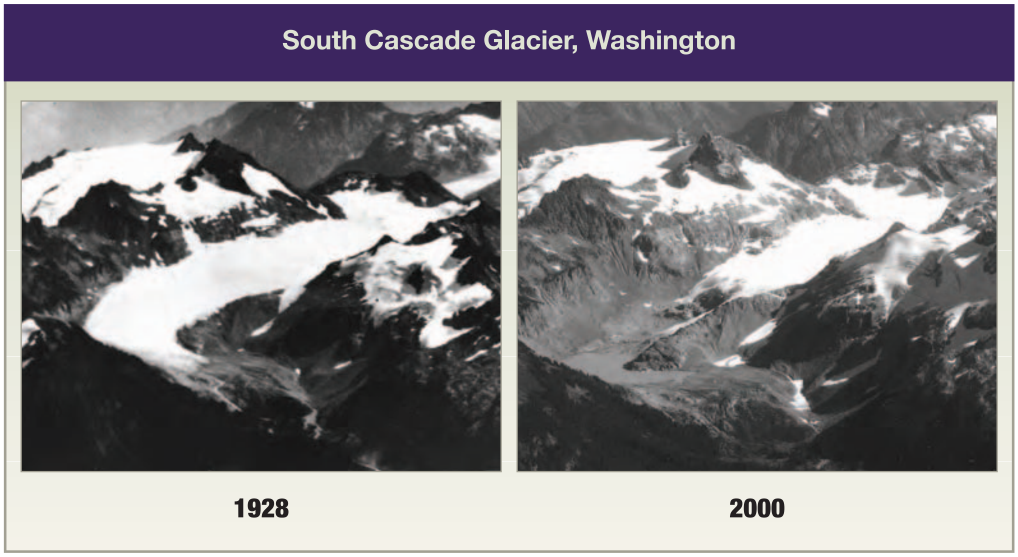


Figure 10: Changing Glacier Mass Balance. Mid-latitude glaciers respond quickly and dramatically to fluctuations in climate. Aerial views of South Cascade Glacier, Washington, in 1928 and 2000, illustrate the magnitude of glacier wastage (negative mass balance) and the terminus retreat that has been characteristic of glaciers in the region. Over this time span, the glacier has lost half its volume and retreated 1.5 km. *Credit: USGS.*

New North American Assimilation System and Reanalysis.[13] Knowledge of the land surface states (e.g., soil moisture, snowpack, evaporation) and the ability to model these states have been major focus areas of CCSP-supported research. The North American Land Data Assimilation System project has created a 1/8-degree modeling system over the continental United States that provides this important land surface information for the purpose of initializing weather and climate models (see <ldas.gsfc.nasa.gov/LDAS8th/LDASdocs/Mitchell2003JD003823.pdf>).

North American Regional Reanalysis.[12] A 25-year North American Regional Reanalysis (NARR; see <wwwt.emc.ncep.noaa.gov/mmb/rreanl>) of historical climate data, covering the period October 1978 through December 2003, was completed in 2004. The regional reanalysis provides a wide range of high-resolution, daily water cycle analysis products such as precipitation, relative humidity, soil moisture, and snow data fields for the 25-year period at 32-km grid scale over North America. The NARR represents advances in regional models and data assimilation that include assimilation of precipitation, direct assimilation of radiances, additional data, and recent developments in modeling, particularly land-surface components. The NARR is a major improvement in both resolution and accuracy over previous reanalysis products.

Global Energy and Water Cycle Experiment – Coordinated Enhanced Observing Period. With support from CCSP agencies, the international Global Energy and Water Cycle Experiment (GEWEX) has coordinated modeling activities and production of new data sets to aid water cycle research. A major GEWEX initiative, the Coordinated Enhanced Observing Period (CEOP; see <www.gewex.org/ceop.htm>), has brought together global observations and model outputs in a consistent framework and provided them to researchers through the Internet. These integrated data sets have enabled new efforts to determine whether the water cycle is accelerating as a result of global change. CEOP is an example of the type of international coordination needed to support the Global Earth Observing System of Systems.

Coupling between Soil Moisture and Seasonal Precipitation.[8] A project supported by CCSP and performed by the GEWEX Global Land/Atmosphere System Study compared climate models to determine the influence of soil moisture on the ability of the model to predict seasonal precipitation and temperature. Although the models differed in the strength of the simulated coupling between soil moisture and precipitation, they were consistent in identifying areas around the globe where knowledge of soil moisture conditions led to enhanced seasonal climate prediction capability (see Figure 11).

International Cooperation on Integrated Global Water Cycle Observations. A CCSP-supported report, *The Integrated Global Water Cycle Observations Theme* (see <ioc.unesco.org/igospartners/Water.htm>), was developed under the framework of

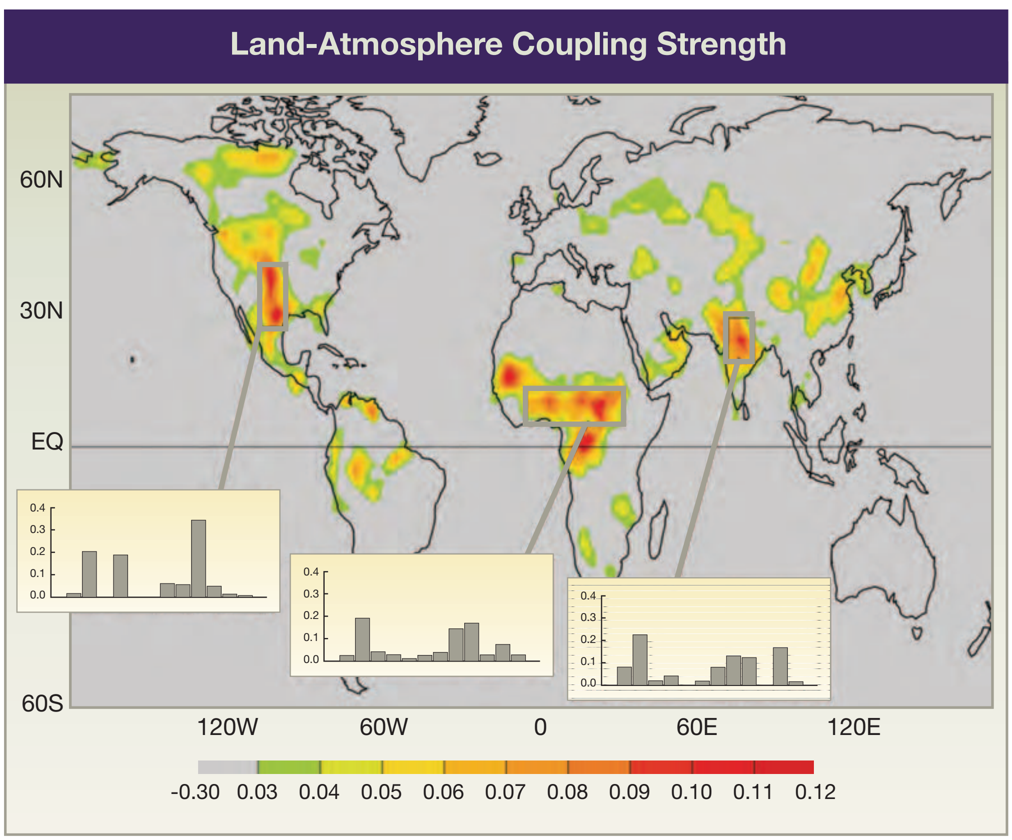
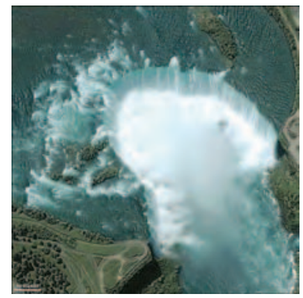


Figure 11: **"Hot Spots" where Soil Moisture Changes can Affect Rainfall**. The red areas are "hot spots" where soil moisture changes can affect rainfall, according to a multi-model study. The bars in the insets show the individual results for 12 climate models, averaged over the indicated regions. According to the insets, the models clearly do not show perfect agreement in the "strength" of the hot spots. Still, many independent models place the hot spots in the same place. The results pertain to Northern Hemisphere summer months June, July, and August. Red areas show the strongest connection between soil moisture and rainfall. The units for the insets are the same as those for the color bar. *Credit: The GLACE Team (Koster* et al.*, 2004).*

the Integrated Global Observing Strategy Partnership and issued in 2004. The report provides a framework for guiding decisions on priorities and strategies for water cycle observations. It also promotes strategies to facilitate the acquisition, processing, and distribution of data products needed for effective management of the world's water resources. The report was developed following extensive international review and workshops held in the United States, Europe, and Japan, and was co-funded by CCSP and the Japan Aerospace Exploration Agency.

Highlights of Plans for FY 2006



In FY 2006, priorities of the CCSP global water cycle research element include continuing U.S. and global observations; field campaigns and experiments; improvements to data integration and analysis systems; diagnostic and prediction model development; and applications to decision-support systems. Several promising results from prior research will be further explored with an aim to provide this knowledge to applications that provide national and global societal benefits. Concurrently, a cohesive research strategy will be implemented to improve the current deficiencies in understanding that exist regarding many aspects of the regional and global water cycle. The program outlined for FY 2006 will lead to near-term improvements in planning, decisionmaking, and resource management activities – a major aim of the program. However, significant unresolved research issues will require longer term effort. To address such research and applications needs, several key initiatives will be launched in FY 2006.

National Hydrological Observatories: Implementing the First of a Network of Comprehensive Observatories for Watershed Data. The Consortium of Universities for the Advancement of Hydrological Science, Inc., is initiating, with assistance from CCSP agencies, planning for the development of basin-scale observatories to support research in hydrology and related sciences. The long-term goal is to establish an integrated network of "hydrological observatories" to bring together hydrological, limnological, meteorological, chemical, ecological, microbial, and other data on soils, landscapes, waterways, wetlands, and lakes, to support researchers probing the integration of watershed processes at scales of thousands of square kilometers. The initial goal is to place watershed data being collected by a wide variety of organizations into a common framework for easy access by all for interdisciplinary research and water resources management. Gaps in current research and operational observing systems will be filled by adding complementary measurements so as to better quantify atmospheric, surface, and subsurface processes in the water cycle, including transport and transformation of chemical species. Progress is being made toward establishing supporting infrastructure and awards will be made in FY 2006 for testing major issues in observatory design.

These activities will address Questions 5.1, 5.2, 5.3, 5.4 of the CCSP Strategic Plan.

Tropical Warm Pool International Cloud Experiment: Improving Understanding of Key Water Cycle Processes. Cirrus clouds are ubiquitous in the tropics and have a large impact on their environment, but the properties of these clouds are poorly understood. A measurement campaign focusing on cirrus clouds is being planned for the region around the Atmospheric Radiation Measurement site in Darwin, Australia, during January-February 2006. The Tropical Warm Pool International Cloud Experiment (TWP-ICE) will employ multiple research aircraft, launch balloon-borne meteorological sensors from an array of sites, and extend the spatial sampling of the Darwin region with additional surface sites (see Figure 12). TWP-ICE will provide a picture of cloud conditions with unprecedented detail for the deep tropics. The data set produced through this effort will be used to evaluate how existing models simulate cloud properties and to improve those models. TWP-ICE has been developed through collaboration among a variety of institutions from the United States (including DOE and NASA), Australia, Europe, Canada, and Japan.

These activities will address Questions 5.2 and 5.3 of the CCSP Strategic Plan.

Tracking Changes in National and Global Water Resources. Promising preliminary research results from the Gravity Recovery and Climate Experiment (GRACE) satellite, a joint U.S.-Germany mission, will be expanded in 2006 to quantify changes in regional water storage (reservoirs and groundwater). In 2004, seasonal and year-to-year changes in water storage at subcontinental scales were identified from GRACE observations, and agreed with best estimates from Land Data Assimilation Systems. GRACE observations, together with advanced gravity anomaly models, provide a powerful new tool to track surface water fluxes from one place to another, and to assess how these fluxes influence climate, weather, and water resource availability. In the past, the measurement of water in large, inaccessible river basins has not been reliable and fluxes in underground aquifers and deep ocean currents have been nearly impossible to measure. Observations of regional mass variations of water on land and in the oceans will assist in interpreting annual signals in long-term sea-level change that have become an important indicator of climate change. Similarly, changes in regional groundwater will provide critical observational "closure" constraints to hydrological models used for water resources management.

These activities will address Questions 5.1, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

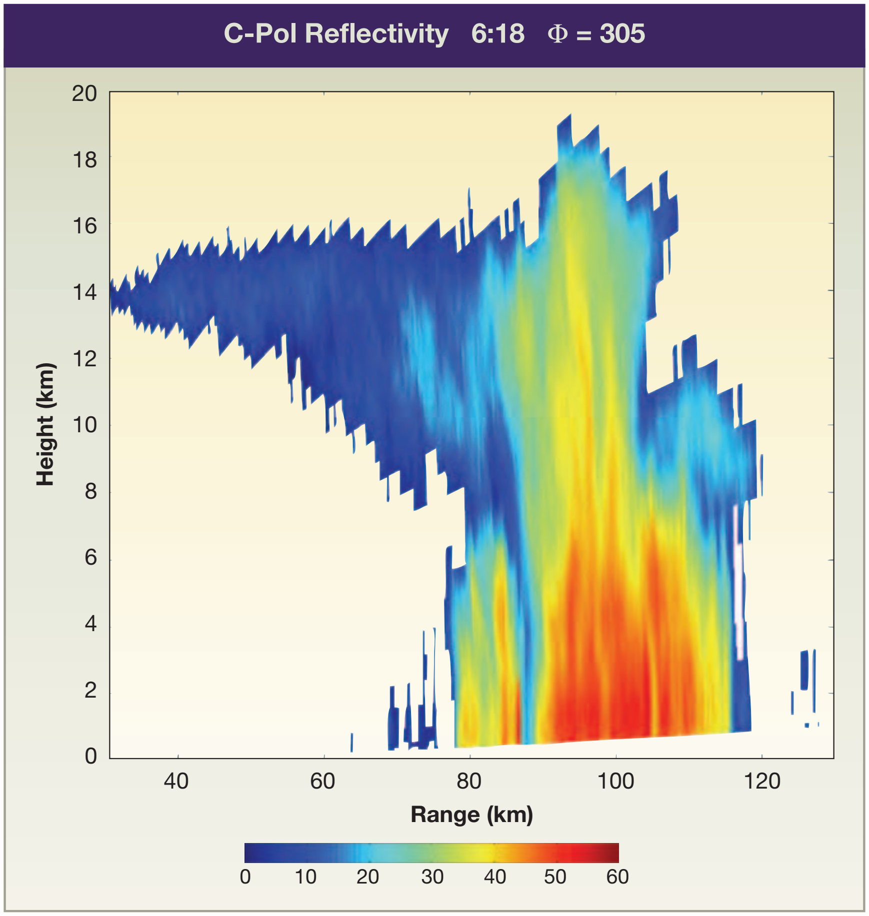


Figure 12: Build-Up to the Wet Phase of the Australian Monsoon. During the wet phase of the Australia monsoon (Dec-Feb) and the build-up to the wet phase (Nov), convection is a common occurrence at Darwin. This image from the centimeter-wavelength radar operated at Darwin illustrates the intense convection that typifies the monsoon build-up period. Such convection may exhibit strong updrafts (reds and yellows in the image) reaching altitudes of 18 km or greater. Convection during the active wet phase of the monsoon exhibits weaker updrafts more representative of oceanic conditions. During TWP-ICE both types of convection will be encountered, providing a means of relating cloud properties to convective strength. *Credit: P. May, Australian Bureau of Meteorology Research Centre.*

Synchronized Measurements to Address Key Uncertainties Associated with the Water and Energy Cycles. With the launch of CALIPSO, CloudSat, and PARASOL, the satellite constellation designated the "A-Train" – composed of those satellites and Aqua and Aura (see Figure 28 in the "Observing and Monitoring the Climate System" chapter later in this volume) – will provide an unprecedented opportunity through FY 2008 for the Earth science community to utilize satellite data to evaluate and improve components of Earth system models. These different instrument platforms, flying in the same orbit minutes apart, will provide multi-platform observations of water and energy cycle processes. The A-Train will be a demonstration of the technological capability to obtain nearly co-located, time-synchronous measurements from a suite of satellites. Teams of scientists have been assembled to take advantage of this unique opportunity. Some of the specific issues that will be addressed are cloud formation/dissipation processes, aerosol-cloud interactions, and cloud-radiation feedback, which are major sources of uncertainty in climate models.

These activities will address Goal 1 of the CCSP modeling strategy and Questions 4.1, 4.2, 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Monitoring Global Tropical Precipitation: The Heat Engine that Drives Global Atmospheric Circulation. The Tropical Rainfall Monitoring Mission (TRMM) satellite will be extended well beyond its design life of 3 years to 2009, thereby providing continued active radar coverage of global tropical rainfall and cloud structure. TRMM, launched in 1997 with the first space-based precipitation radar together with a co-located TRMM Microwave Imager (TMI), among other instruments, has worked flawlessly and provided substantially improved data about cloud structure and new processing algorithms for passive microwave instruments aboard other satellites [e.g., the Special Sensor Microwave/Imager (SSM/I)]. Progressively improved algorithms derived from TRMM research will continue to be used to reprocess SSM/I data from previous (20+) years to obtain more accurate estimates of global tropical precipitation climatology and time series of tropical precipitation variability and change. Also being explored are requirements for a follow-on "operational" satellite system to provide data comparable to TRMM and to enable the optimal use of data from the Global Precipitation Mission (GPM). GPM represents the next-generation follow-on research spacecraft to TRMM, planned for launch by the end of the decade.

These activities will address Questions 5.1 and 5.3 of the CCSP Strategic Plan.

Observing and Resolving Soil Moisture: A Critical Uncertainty in Earth/Climate Models and Operational Applications. A new thrust in the Second Global Soil Wetness Project (GSWP-2) under the rubric of the international GEWEX Modeling and Prediction Panel is to better link land-surface modeling with remote-sensing applications. This will be done by expanding the validation and assimilation capabilities of current Land Surface Schemes (LSS) at a spatial resolution of about 1 degree (~100 km) beyond the few years where *in situ* data are readily available. LSS will continue to be examined for their ability to simulate brightness temperature, assessed by comparing airborne measurements from several large-scale campaigns held during GSWP-2. Such an assessment is a prototype of LSS validation on a global scale, which is necessary for taking advantage of future satellite-based L-band radiometry from NASA's HYDROS satellite mission, the European Space Agency's Soil Moisture-Ocean Salinity mission, and the NASA Aquarius (ocean salinity/soil moisture) mission. HYDROS offers the unique advantage of carrying both active and passive microwave instruments.

These activities will address Questions 5.1, 5.2, 5.3, 5.4, 5.5 of the CCSP Strategic Plan.

Synergistic Observations, Research, and Modeling: Bedrock to Boundary Layer and Beyond. One of the roadblocks to enhancing water cycle understanding is the lack of comprehensive coincident measurements of all aspects of the continental water cycle. This includes observations of subsurface hydrology (groundwater to the bedrock, soil moisture, and chemistry), the land surface (e.g., runoff, vegetation and evapotranspiration, surface exchange fluxes of heat, momentum, and moisture, and radiation balance), the atmosphere (e.g., water vapor, winds, thermodynamics, cloud radiative forcing, and precipitation), and water consumption, distribution, and quality, among others. In FY 2006, the Science Steering Group for the CCSP global water cycle research element and the broader science community will develop an "integrating" strategic implementation plan to address these issues. The plan will be one of the central features of CCSP's implementation of the water cycle science component, and will outline a strategy for achieving near-term priorities while laying the groundwork for targeting longer term goals. Observing systems will be designed within the construct of a seamless modeling framework, and associated data and information synthesis and management systems. The outcome of this research, spanning the next decade, will be an essential part of an integrated end-to-end approach to help apply operational and research-based water cycle observations, model predictions, and data assimilation products to decision-support tools that are developed and used by the operational applications community, including planners and managers of natural and economic resources.

These activities will address Questions 5.1 through 5.5 of the CCSP Strategic Plan.

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