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 water cycle is essential to life on Earth. As a result of complex interactions, the water cycle acts as an integrator within the Earth/climate system, controlling climate variability and maintaining a suitable climate for life. The water cycle manifests itself through many processes and phenomena, such as clouds and precipitation; ocean-atmosphere, cryosphere-atmosphere, and land-atmosphere interactions; mountain snow packs; groundwater; and extreme events such as droughts and floods.

Inadequate understanding of and limited ability to model and predict water cycle processes and their associated feedbacks account for many of the uncertainties associated with our understanding of long-term changes in the climate system and their potential impacts, as described by the IPCC. For example, clouds, precipitation, and water vapor produce feedbacks that alter surface and atmospheric heating and cooling rates, and the redistribution of the associated heat sources and sinks leads to adjustments in atmospheric circulation, evaporation, and precipitation patterns.

Clean water is an essential resource for human life, health, economic growth, and the vitality of ecosystems. From social and economic perspectives, the needs for water supplies adequate for human uses—such as drinking water, industry, irrigated agriculture, hydropower, waste disposal, and the protection of human and ecosystem health—are critical. Water supplies are subject to a range of stresses, such as from population growth, pollution, and industrial and urban development. These stresses can be affected by climate variations and changes that alter the hydrologic cycle in ways that are currently not predicted with sufficient accuracy for decisionmakers.

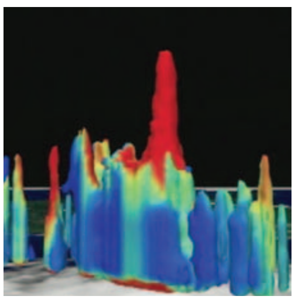
Advances in observing techniques, combined with increased computing power and improved numerical models, now offer new opportunities for significant scientific progress. Recently, for example, credible predictions of seasonal variations in the water cycle have been produced for the western United States and Florida. Along with the growing ability to provide advance notice of extreme hydrologic events, this forecast capability provides new options for social and economic development and resource and ecosystem management. In addition, recently launched NASA satellites such as Terra, Aqua, GRACE, and ICESat, among others, will substantially increase the detailed data needed to better understand and model global and regional water cycle processes.

Highlights of Recent Research

Highlights of recent research supported by CCSP participating agencies follow.

Cloud feedback effects. A combination of improved models and better measurement technology is closing the gap between observed and modeled quantification of radiative fluxes in the atmosphere (flows of incoming solar radiation and outgoing radiation from the Earth through the atmosphere). These new results are helping to improve the radiative transfer calculations in climate models being developed for the start of the next international assessment by the IPCC.

The radiative transfer components of climate models account for how water vapor, other gases, and cloud droplets scatter and absorb solar radiation and absorb and reradiate infrared radiation. Studies in the mid-1990s indicated that clouds absorbed roughly 40% more sunlight than calculated by climate models, suggesting that the inaccuracy of model calculations of radiation absorption by clouds was undermining the ability of the models to simulate climate correctly. However, new model calculations of cloud absorption, using state-of-the-art radiative transfer models, closely match recently analyzed cloud observation data from DOE's Atmospheric Radiation Measurement Enhanced Shortwave Experiment-II, which was conducted at a site in Oklahoma. This data set was unique in its redundant measurements and high quality control. In addition, studies have shown that, by modifying models to account for radiation absorbed by microscopic aerosol particles such as dust and soot, the gap between models and observations can be narrowed even further.



Multi-scale simulation of cloud effects on climate. The global circulation of the atmosphere has been simulated using a radically new kind of mathematical model that simulates cloud processes directly. A high-resolution cloud model is run "inside" the lower resolution global model to create a "multi-scale modeling framework" (MMF). Results from the MMF show major improvements, relative to earlier models, for the simulation of many kinds of weather and climate systems, including the most powerful cloud systems in the tropics. Particularly encouraging is the improved representation of the diurnal cycle of precipitation. This modeling tool is one of several important research components being applied to achieve a better quantitative understanding of climate feedbacks related to atmospheric convection and hydrologic and cloud processes. The ever-increasing availability of new computational advances as well as high-quality observational data from field programs is making such advances possible (see, for example, Figure 11).

Water vapor measurement. Because water vapor is by far the most abundant of the greenhouse gases, accurate water vapor measurements are essential for understanding atmospheric processes and representing and evaluating them in regional and global climate models. Instruments and observational protocols are needed to measure water vapor accurately. Researchers have succeeded in reducing measurement uncertainties in water vapor concentrations from greater than 25% to less than 3% using ground-based instrumentation, such as Raman lidar and microwave radiometer (see Figure 12).

ICESat launched. The Ice, Clouds, and Land Elevation Satellite (ICESat) was successfully launched in January 2003. This Earth Observing System mission—covering the Arctic, the Antarctic, continental high elevations, and the oceans—measures water cycle variables, including ice sheet mass balance, cloud and aerosol heights, and land topography and vegetation characteristics. ICESat provides, primarily, land-ice and sea-ice altimetry products, with cloud/aerosol lidar and land/vegetation altimetry as secondary products. ICESat will provide multi-year elevation data needed to determine

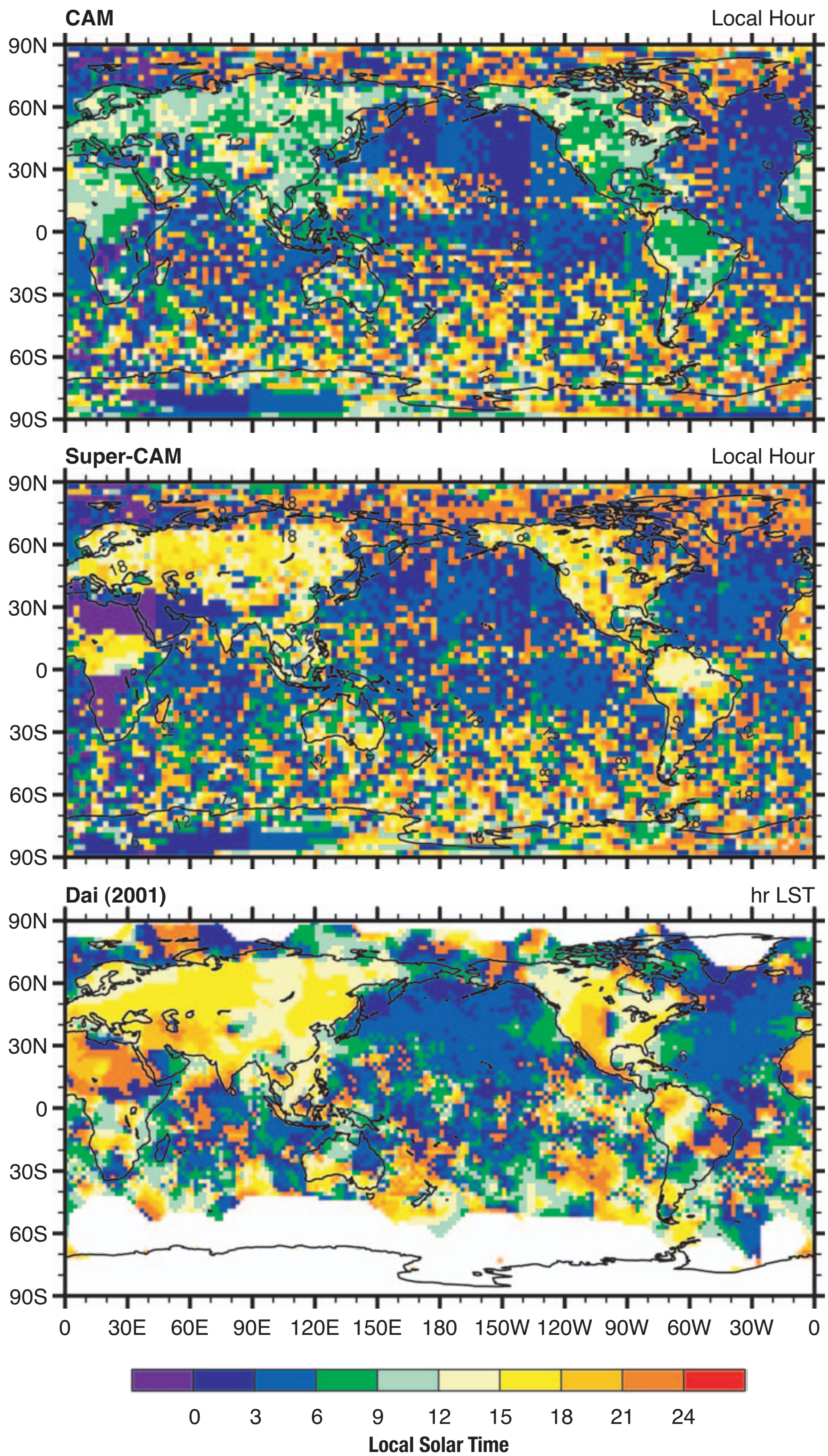


Figure 11:
Modeling the diurnal cycle of precipitation. The mean June-July-August local solar time of non-drizzle precipitation frequency maximum has been simulated with the standard Community Atmosphere Model (CAM) (upper panel); super-parameterization CAM (middle panel); and from observational data set by Dai (bottom panel). Non-drizzle precipitation was defined as producing mean precipitation rate in excess of 1 mm per day over a 3-hour interval.
Source: From Khairoutdinov et al. 2004, J. Atmos. Sci., submitted.

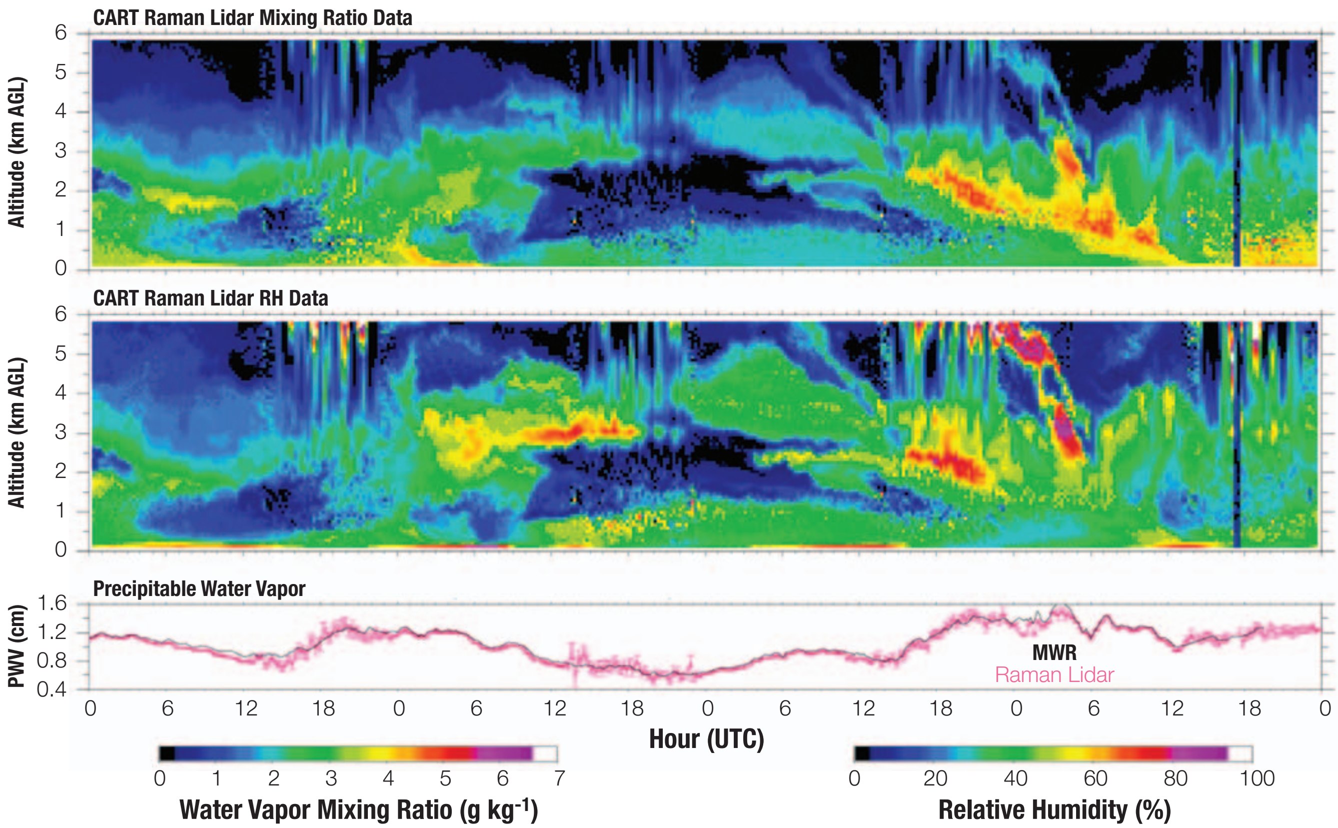


Figure 12: Laser technology captures continuous, vertical distributions of water vapor over the Atmospheric Radiation Measurement's Southern Great Plains Site for the 29 November - 2 December 2002 time frame. The figure represents three measurements that are important for climate studies: (a) ratio of water vapor to dry air (CART Raman Lidar Mixing Ratio Data); (b) relative humidity (CART Raman Lidar RH Data); and (c) the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending from the surface to the top of the atmosphere (precipitable water vapor). *Credit: David Turner, University of Wisconsin.*

ice sheet mass balance around the globe, in addition to the polar-specific coverage over the Greenland and Antarctic ice sheets. ICESat observations, together with those of the Terra and Aqua satellites, will more accurately quantify the changes in the Greenland ice sheet and the interannual changes of Arctic ice. These regions, identified by models to be highly sensitive to climate warming, already show signs of a strong climate change signal with a shrinking of perennial ice-covered regions.

Enhanced sea ice observations. Data from the EOS Aqua satellite are providing the research community with sea ice data products at a higher spatial resolution and a greater spectral range than previously possible. To make these data products a useful research tool, a comprehensive sea ice validation program is currently underway. An Arctic field campaign with the NASA P3 aircraft was completed in March 2003. Enhanced calibration of satellite microwave sensors will permit a more accurate monitoring of sea ice variability and provide data for the validation of coupled models that require improved sea ice component models in order to better understand and predict polar responses to global climate change.

Water cycle observation from space. NASA's Gravity Recovery and Climate Experiment (GRACE) satellite—successfully launched in March 2002, to measure both the static and time-variable components of the Earth's gravity field—has delivered (in mid-2003) the first global analysis of data showing the distribution of gravity variations around the world. Due to an uneven distribution of mass inside the Earth, the Earth's gravity field is not uniform. The gravity variations that GRACE will study include changes due to surface and deep currents in the ocean; runoff and groundwater storage on land masses; exchanges between ice sheets or glaciers and the oceans; and variations of mass within the Earth.

Future data analysis and applications based on measurements from GRACE will provide information on changes in the extent and volume of water stored in continental water bodies (large reservoirs, lakes, and groundwater), as well as other physical changes, such as movement of warm water zones in the Pacific Ocean (El Niño) and shifting tectonic plates. Simulations of GRACE observations show that the time variations in the water budget of the Mississippi River basin, for example, are well-captured. Remote sensing of changes in water storage has potential applications to monitoring and management of regional water supplies, as well as national and international resource assessment and planning activities.

Water cycle-carbon cycle interactions. A number of recent studies demonstrated intimate links between the water cycle, the carbon cycle, and climate. A combination

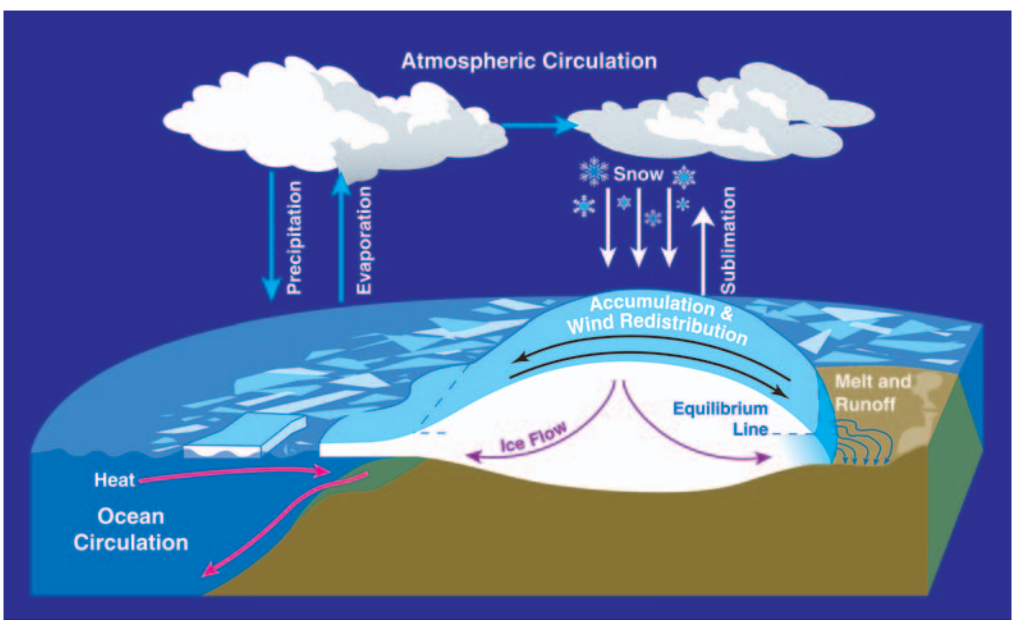


Figure 13: Future changes in ice sheet mass balance will be a complex function of accumulation and melting as well as dynamic ice sheet behavior. Sea level response is still not well understood. ICESat observations will help answer important questions about trends that affect the ice mass balance and sea level change. *Credit: NASA.*

of data analysis and model integrations and diagnostics suggests that approximately 60% of the increase in terrestrial carbon sequestration in North America may be attributable to increases in rainfall over the North American continent. Previously, most of the increased carbon sequestration in the Northern Hemisphere was thought to be due to a combination of increases in temperature and the direct fertilization effect of increased atmospheric CO_2 concentration. This study's results indicate that changes in precipitation may be at least as important.

A recent study of chemical weathering, using a combination of precipitation, streamflow, and alkalinity measurements from USGS, showed that carbon export, in the form of alkalinity, has increased along with levels of streamflow and precipitation in the Mississippi River basin. Chemical weathering converts CO_2 into dissolved bicarbonate or carbonate that is then transported by rivers to the ocean. River transport of alkalinity from land to ocean is a major source of oceanic alkalinity and thus is a regulator of the carbonate saturation state of the oceans. This has implications for the global carbon cycle and the function of oceans as carbon sinks.

A third study by a multidisciplinary group from government agencies, universities, and the private sector analyzed the fires associated with the 1997-1998 El Niño drought conditions using satellite observations, together with output from biogeochemical and atmospheric chemistry transport models and observed carbon concentrations at flask stations. The study found that during the 1997-1998 El Niño event, fire emissions of carbon increased significantly (2.1 ± 0.8 PgC, or $66 \pm 24\%$ of the CO_2 growth rate anomaly). The study suggests that the variability and intensity of the water and energy cycle on interannual time scales may be among the most critical factors regulating carbon budgets. For example, when conditions support fires, regions that have long served as carbon sinks may suddenly become carbon sources.

Modeling the global water and energy cycles and their regional components. The Global Energy and Water Cycle Experiment (GEWEX) Continental-scale International Project successfully completed water and energy budget studies for the Mississippi River Basin. Results indicate that the water and energy budgets over the Mississippi River Basin can be closed to within 15%. Water and energy budgets account for the amount of water and energy entering a region, how they are partitioned among their various components (e.g., evaporation, runoff, groundwater), and the amount leaving the region. To close a budget, it is necessary to understand the processes that control inflow, partitioning, and outflow, and to have sufficient data on key variables. In addition to establishing benchmarks for future modeling studies, data and results of these studies will be used in initializing and validating regional climate models.

Prediction of warm season rain. In order to better understand the processes influencing warm season rain in the southwestern United States, process and modeling studies have been carried out that explore the role of the North American Monsoon system in the water budget stores over the region. These studies relied upon fine-resolution precipitation data products and improved representations of land processes in models during the monsoon period, and examined the effects of model resolution on the simulation of summer mountain region precipitation processes. New process understanding that results from these studies will improve simulation and monthly to seasonal prediction of the monsoon and regional water resources.

Evaluation of water cycle prediction products for decision support. A joint NOAA/NASA project on improving water demand analysis and prediction for U.S. Bureau of Reclamation water managers is designed to improve estimates of evapotranspiration (loss of water from the soil) in New Mexico. The project uses satellite remote sensing, radar, and surface-based observations, and numerical forecasts and surface modeling, to integrate Land Data Assimilation System information into water operations decision support systems, and displays decision data on the Web. Bureau of Reclamation water managers, water conservancy districts, and farmers may access the information daily to help them conserve the State's extremely limited water resources.

Highlights of Plans for FY 2004 and FY 2005

The CCSP will continue to improve the capabilities for measuring important aspects of the global water cycle and will conduct a number of important research and analysis projects. Key research plans for FY2004 and FY2005 follow.

Integrated hydrologic database development. A major obstacle to research on the water cycle is the wide range in the types of data sets. Data sets are created by a variety of agencies for a variety of purposes. Integrating these data would extend and expand their usefulness for addressing important scientific, management, and policy-related questions that cross traditional disciplinary boundaries. Disparities in existing data that present challenges to integration include scale, both temporal and spatial, and type, whether continuous or discrete. A new effort will be initiated in FY 2004 to integrate these disparate data sets for general use in hydrologic research and water resources management.

These activities will address all five strategic research questions on the Global Water Cycle in the CCSP Strategic Plan, particularly Questions 5.3, 5.4, and 5.5, and will lay the groundwork for implementation of many products.

Integrated global observing strategy and coordinated data sets. Several U.S. agencies will cooperate in an international effort to establish an integrated global observing strategy for water cycle variables as a component of the world climate research agenda. Observation of water cycle variables has been identified as an important weakness in climate prediction, particularly with respect to regional manifestations of variability and change. A coordinated strategy for observing these variables will enable more effective deployment of observational resources. The strategy will provide input to the Group on Earth Observations (GEO) to promote consistency with the Earth observation system under development by GEO. In FY 2004, a Water Cycle Theme report will be published and an international management structure for the program will be created. The Coordinated Enhanced Observing Period (CEOP) will be the program's first focus, and an initial report on results will be published in FY 2005.

Participants in the Coordinated Enhanced Observing Period, which include national weather centers, space agencies, other government agencies, and university research centers, will release integrated global data sets, covering the period 1 October 2001 to 31 December 2004. The preliminary data set (October to December 2001) is being used now in process studies, model comparisons, and related research. A second set (2002 to 2003) is being processed and archived for release in FY 2004, and a third set (2003 to 2004) is planned for release in FY 2005. Data include satellite observations, measurements made at more than 60 globally distributed GEWEX reference sites, and Model Output Time Series (MOLTS) data from various global modeling centers. The data sets will be useful in a wide range of applications, including improving predictions associated with the North American Monsoon System.

These activities will address Questions 5.1 (first product), 5.2 (fourth product), 5.3, and 5.4 of the CCSP Strategic Plan.

Characterizing atmospheric water vapor. A new satellite, scheduled for launch in 2004, will provide a platform for measuring upper tropospheric water vapor profiles—information that is essential for understanding climate and water cycle variability. In FY 2005, the Microwave Limb Sounder (MLS) on NASA's EOS-Aura will begin transmitting its first streams of data on lower stratospheric and upper tropospheric temperature and water vapor, in addition to measurements of atmospheric chemistry. Before MLS, water vapor profiles in the lower stratosphere and upper troposphere were difficult to observe reliably on a global scale, but the Upper Atmosphere Research Satellite (UARS) demonstrated that MLS is capable of measuring upper troposphere water vapor profiles, even in the presence of cirrus clouds. In addition, MLS is unique in its ability to measure cirrus ice content. The HIRDLS (High-Resolution Dynamics Limb Sounder) on EOS-Aura will complement MLS by profiling the upper troposphere, stratosphere, and mesosphere to determine temperature and concentrations of ozone, water vapor, and various chemical species. The simultaneous measurements of upper tropospheric water vapor, ice content, and temperature, under all conditions and with good vertical resolution, will be of great value for improving understanding of processes (such as El Niño) affecting the distribution of atmospheric water, climate variability, and tropospheric-stratospheric exchange.

These activities will address Questions 5.1 (second product) and 5.2 of the CCSP Strategic Plan.

Reprocessing of global climate data. In FY 2005, the retrospective global time series of key water and energy cycle parameters will be extended by reprocessing data using new algorithms. For example, an extended global precipitation data time series will be produced using algorithms derived from experience with the Tropical Rainfall Measuring Mission (TRMM) satellite and other experimental platforms.

These activities will address Questions 5.1 (fourth product) and 5.3 of the CCSP Strategic Plan.

Reanalysis of regional climate data. Regional reanalysis of historical observations, covering the period 1979 through 2003, will be completed in FY 2004. The period 1979 through 2001 is already finished. The regional reanalysis produces a wide range of high-resolution, daily water cycle analysis products at 3-hourly intervals, such as precipitation, relative humidity, moisture flux, soil moisture, and snowpack fields at 32-km spatial resolution over North America, as well as Central America. These analysis products provide opportunities to analyze climatological features of spatial and temporal variability in the water cycle and improve characterization of land states for initializing predictions at seasonal to interannual time scales. The North American regional reanalysis represents advances in regional models and data assimilation that include assimilation of precipitation, direct assimilation of radiances, additional observation types, and recent developments in modeling, particularly land-surface components. When completed, the North American data set will be the best available for a variety of studies and applications regarding climate, water resources, weather prediction, predictability, and other applications. Regional reanalysis will continue in real-time after the 25-year data set is complete, and will produce forecasts at regular intervals for use in predictability studies.

These activities will address Questions 5.1 and 5.3 (first product) of the CCSP Strategic Plan.

Launch of Cloudsat and CALIPSO satellites. Two Earth System Science Pathfinder (ESSP) satellites addressing global three-dimensional distributions of aerosols and clouds are currently scheduled for launch in mid-FY 2005. These are the joint NASA-French CALIPSO mission to study aerosols and thin clouds, and the joint NASA-U.S. Air Force-Canadian Cloudsat mission to study a broader range of clouds. These satellites will fly as part of a constellation of satellites in polar orbit, with equatorial crossing times within approximately 15 minutes of each other and a number of other NASA satellites measuring atmospheric properties. The integrated impact of this constellation—known as the "A-train" because of the names of other satellites in

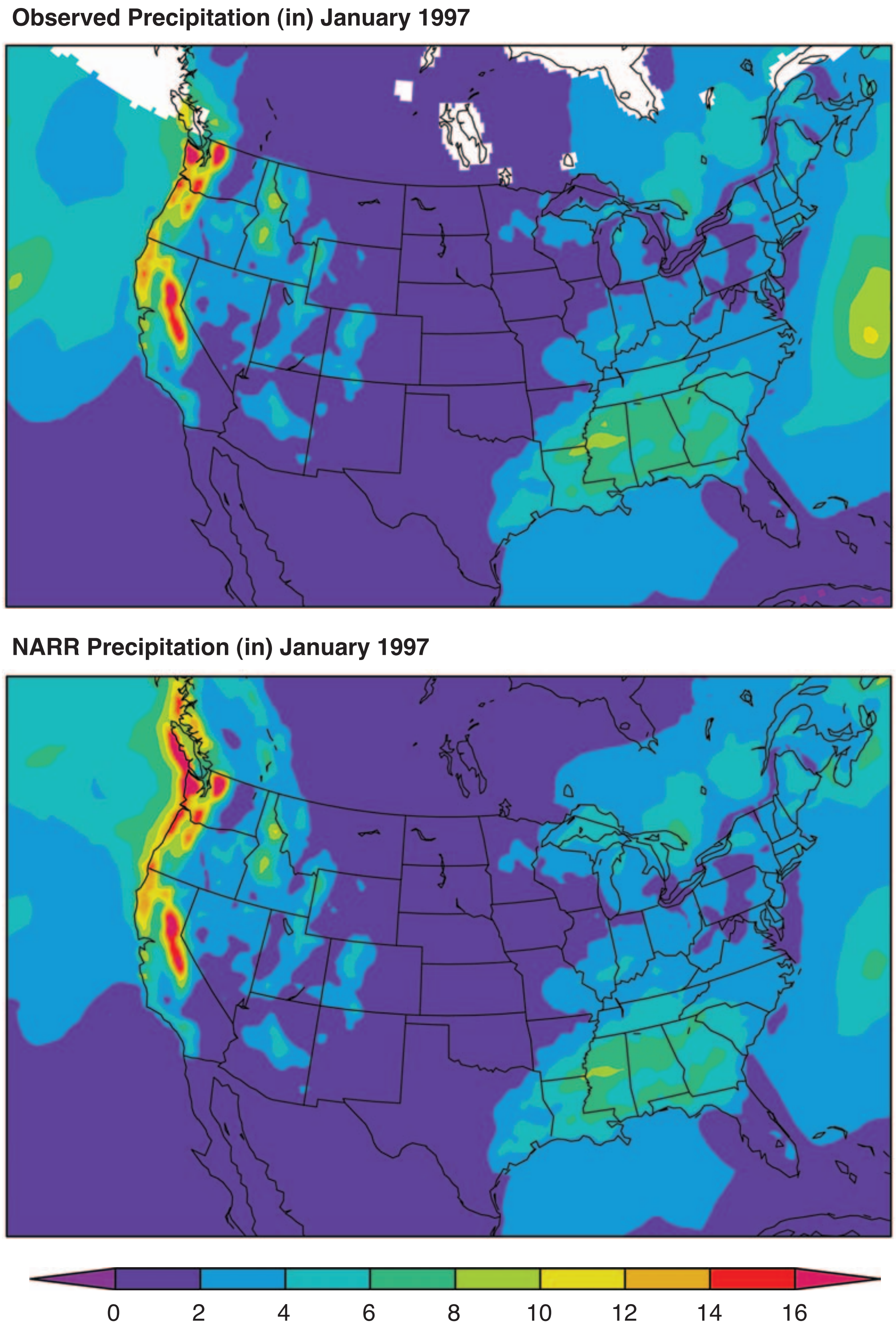
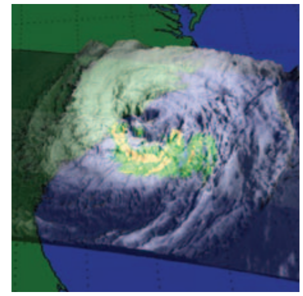


Figure 14: Assimilation of observed precipitation is the most important data addition to the North American Regional Reanalysis (NARR), because successful assimilation of these observations enables more realistic modeling of the hydrological cycle than otherwise would be possible. This figure shows a comparison, during a strong El Niño event (January 1997), over North America of analyzed precipitation based on observations (top panel) and the NARR precipitation output (bottom panel). The color scale indicates inches per month. The comparison shows extremely high agreement over land, even over the complex western topography. The regional reanalysis provides coupled atmospheric and land water cycle components that include preciptation fields in much better agreement with observed precipitation fields than previously available over North America. *Credit: NOAA/National Weather Service/National Centers for Environmental Prediction.*

the constellation (Aqua, Aura)—will be to improve significantly understanding of the relationship between atmospheric temperature, water vapor, aerosols, and clouds.

These activities will address Questions 5.1 and 5.2 of the CCSP Strategic Plan.



Global precipitation monitoring. Planning will continue toward the design and implementation of a Global Precipitation Mission (GPM) satellite. The GPM will be the forward, and more advanced and comprehensive, replacement to the present suite of precipitation measurements by TRMM and SSM/I, among others. TRMM is likely to be de-orbited in 2004 because of a lack of fuel; however, the satellite has already successfully exceeded its planned life span by a substantial margin. The current vision—by NASA and its international partners in Japan and Europe—calls for a constellation of eight satellites carrying some form of passive microwave radiometer (likely a combination of new lightweight satellites and operational/experimental satellites) and a ninth "core" satellite, carrying a dual frequency radar and an advanced, multi-frequency passive microwave radiometer. The constellation is designed to provide at least 3-hour sampling at any spot on the globe for relevant measurements of internal cloud-precipitation microphysical processes and the "training and calibrating" information for retrieval algorithms. The GPM program will involve other international partners, scientific agencies and institutions in the United States, and individual scientists from academia, government, and the private sector to fulfill mission goals and establish a foundation for eventual development of an internationally organized, operational global precipitation observing system. The United Nations has identified this mission as a foremost candidate for its Peaceful Uses of Space Program.

These activities will address Questions 5.1 and 5.3 (seventh product) of the CCSP Strategic Plan.

Cloud feedback processes. Cloud feedback processes will be examined in studies using satellite and *in situ* data (e.g., from Atmospheric Radiation Measurement sites), and results will be incorporated into global climate models to improve the representation of these processes. The very different response of subtropical boundary layer clouds to the doubling of CO_2 in two global climate models (GCMs) will be examined by using observational constraints and by closely examining the various physical parameterizations involved. In addition, cloud feedbacks in tropical convective cloud regimes will be studied. Diagnostic studies based on regional and global observations, single-column model analysis and modeling efforts, GCM sensitivity studies, and interchanges of parameterization schemes between models will be carried out. Better representation of cloud feedback processes in climate models should reduce uncertainties in climate projections.

These activities will address Question 5.2 (first product) of the CCSP Strategic Plan.

Impacts of climate-related hydrologic and water temperature changes. Changes in precipitation and temperature associated with climate change may have direct effects on the concentrations of pollutants and pathogens in surface and ground waters. These changes could have ramifications for aquatic ecosystems, drinking water, human recreational uses, and the cost of environmental protection. In 2004, a project will be completed evaluating how climate-related hydrologic and water temperature changes may affect the costs of attaining water quality standards at publicly owned sewage treatment works in the Great Lakes region. Results from this project will include: 1) identification of water quality-limited watersheds in the Great Lakes and evaluation of their vulnerabilities to climate change; and 2) estimates of changes in treatment efficiency required, and associated costs, for continued compliance under different water quality standards and climate change scenarios. In FY 2005, a report will be completed to evaluate the effects of global changes on drinking water infrastructure, wastewater treatment, and surface water/groundwater characteristics.

These activities will address Questions 5.4 (fourth product) and 5.5 of the CCSP Strategic Plan.

Moisture monitoring tool for land management. An experimental surface and subsurface moisture-monitoring product for land resource management is being developed and tested. As part of the effort to build a national drought monitoring system, researchers in California are developing a technique, based on a moisture index, for estimating the likelihood of drought-related threats, such as forest fires and loss of agricultural crops. In FY 2004, the new tools will be incorporated into regional and national drought monitoring systems.

These activities will address Question 5.5 (first product) of the CCSP Strategic Plan.

Climate predictions in water management. Water managers need more accurate and timely forecasts of water supplies and demands to manage limited, and often over-allocated, water resources in the semi-arid West. Thus, an experimental on-line decision support tool designed to provide users with a description of streamflow conditions and their accompanying probabilities in the Pacific Northwest, from near-term climate predictions and long-term projections, is being developed, demonstrated, and deployed in the Columbia River Basin. Data assimilation systems and land surface models developed under the CCSP by NASA, NOAA, and other agencies and universities will be integrated with river system management decision support systems developed by the Bureau of Reclamation and used by water managers to make daily to seasonal water operations decisions. Tests of prototype systems in FY 2004 will be followed by routine integration of forecasts in FY 2005, depending upon the range of uncertainty associated with the streamflow forecasts and water demand forecasts. If successful, the integrated forecasting and decision support system will be extended to other major river systems of the West.

These activities will address Question 5.5 (second product) of the CCSP Strategic Plan.

Forecast tools on the Web. Web-based tools will be refined to improve communication and usability of climate and water forecasts. One of the major barriers to the effective use of forecasts in policy and resource management decisions is the failure of forecast products to communicate to potential users the nature of their associated uncertainty, its meaning and value. In FY 2004, tools designed to help users of predictions over a range of time scales understand and evaluate forecast uncertainties will be enhanced on the basis of tests that have been carried out with users in Arizona.

These activities will address Question 5.5 (third product) of the CCSP Strategic Plan.