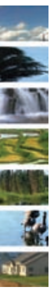


3 | Global Water Cycle

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?

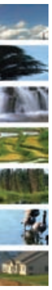
See Chapter 5 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

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 2007 include the planning and implementation 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 that 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. Strategies for implementation include 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 Observation System of Systems (GEOSS) and its U.S. counterpart, the International Earth Observing System (IEOS).

The global water cycle research element continues to pursue 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. 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 moisture), and rainstorms. Results from these studies show promise of leading to earlier (and more accurate) predictions, improved ability to assess hazards and risks of extremes such as floods and droughts, and 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 tests predictions and data products in real decisionmaking contexts, demonstrates techniques and their effectiveness to potential users, and provides 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.



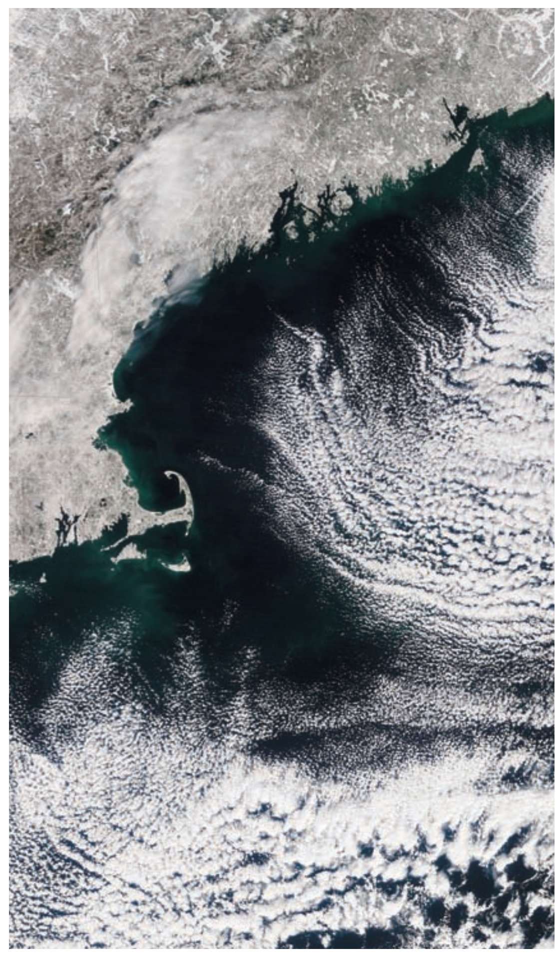
HIGHLIGHTS OF RECENT RESEARCH

Selected highlights of recent research supported by the CCSP-participating agencies follow. These research results address the strategic research questions on the global water cycle identified in the *CCSP Strategic Plan*. Due to the overlap between the global water cycle and other CCSP elements, some themes such as water vapor-radiation feedback, an important component of global water cycle research, are elaborated in other chapters of this publication rather than here.

Modeling and Simulation of Cloud Processes and Cloud Systems.[11,12,15,18,23]

Multi-Scale Simulations of Clouds. Researchers have been experimenting with a global atmospheric model in which the conventional cloud parameterizations are replaced, in each grid column, by a two-dimensional cloud-resolving model. Figure 12 shows that the model produces a simulation of upper tropospheric cloudiness that is much more realistic than a control run.

New Shallow Cloud Convection Scheme. By comparing regional model simulations with the observations collected at the Atmospheric Radiation Measurement (ARM) Southern Great Plains and Tropical Western Pacific sites, scientists evaluated the overall performance of a recently developed shallow cumulus parameterization scheme



Simulations and Observations of the High-Level Cloud Fraction

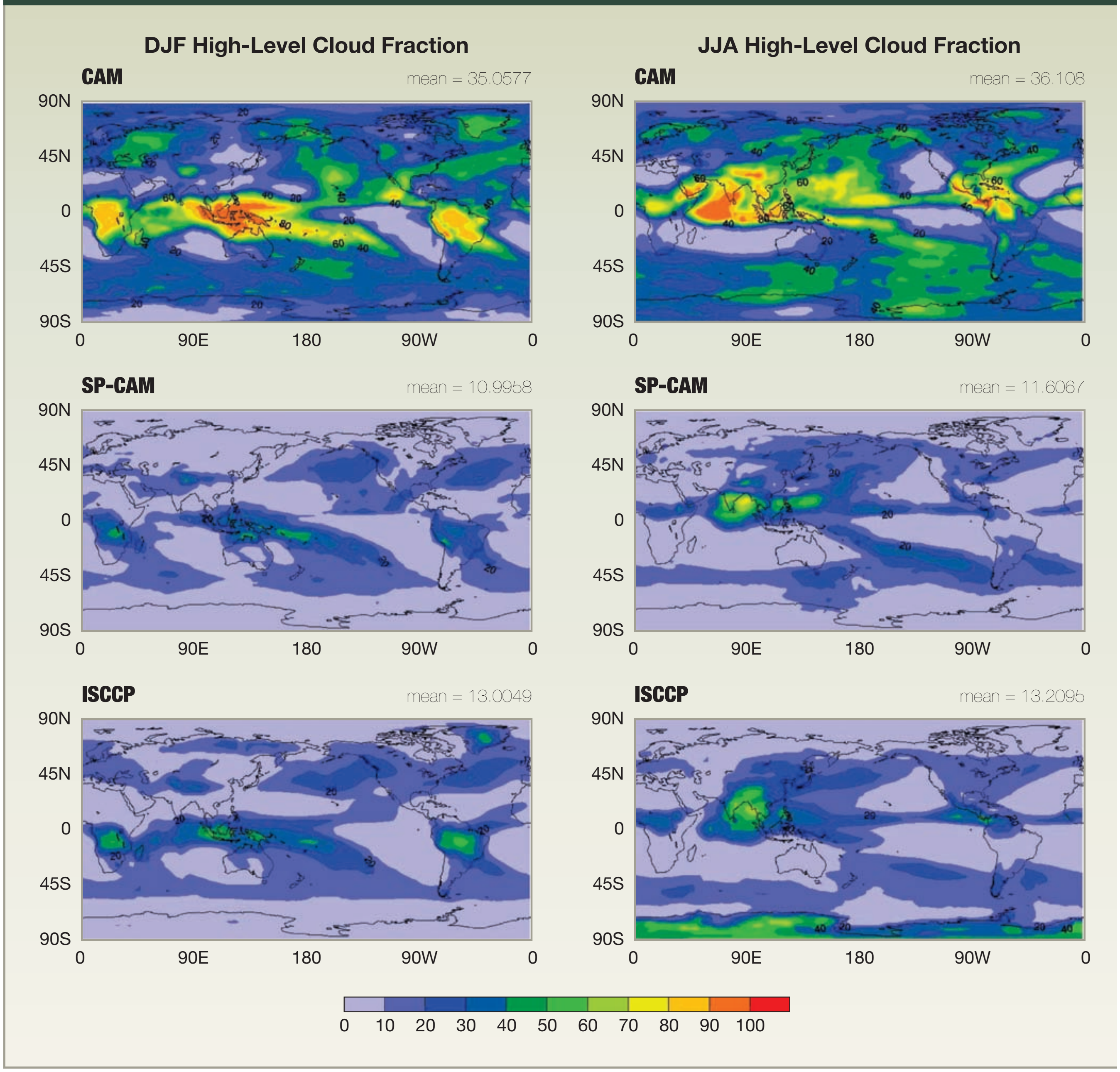
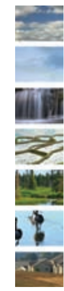


Figure 12: Simulations and Observations of the High-Level Cloud Fraction (above 400 mb). The left panels show results for December–February (DJF), and the right panels for June–August (JJA). The top two panels are from a control run (CAM); the middle two panels are from the experimental model (SP-CAM); and the bottom two panels show observations from the International Satellite Cloud Climatology Project (ISCCP). *Credit: M. Khairoutdinov, D. Randall, and C. DeMott, Colorado State University (reproduced from* **Journal of the Atmospheric Sciences** *with permission from the American Meteorological Society).*



under different meteorological conditions (see Figure 13). The simulations indicate that the shallow cumulus scheme can accurately simulate both marine shallow cumuli and the observed diurnal cycle of continental shallow cumuli. Sub-grid cloud properties, the resolved thermodynamic structures, and the surface energy budget are simulated well by the model.

Diagnostic Simulations of Arctic Cloud Systems. Scientists used measurements made as part of the ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) to evaluate the performance of the Community Atmosphere Model (CAM3) of the National Corporation for Atmospheric Research (NCAR), the Atmosphere Model (AM2) of NOAA's Geophysical Fluid Dynamics Laboratory, and the weather forecast model of

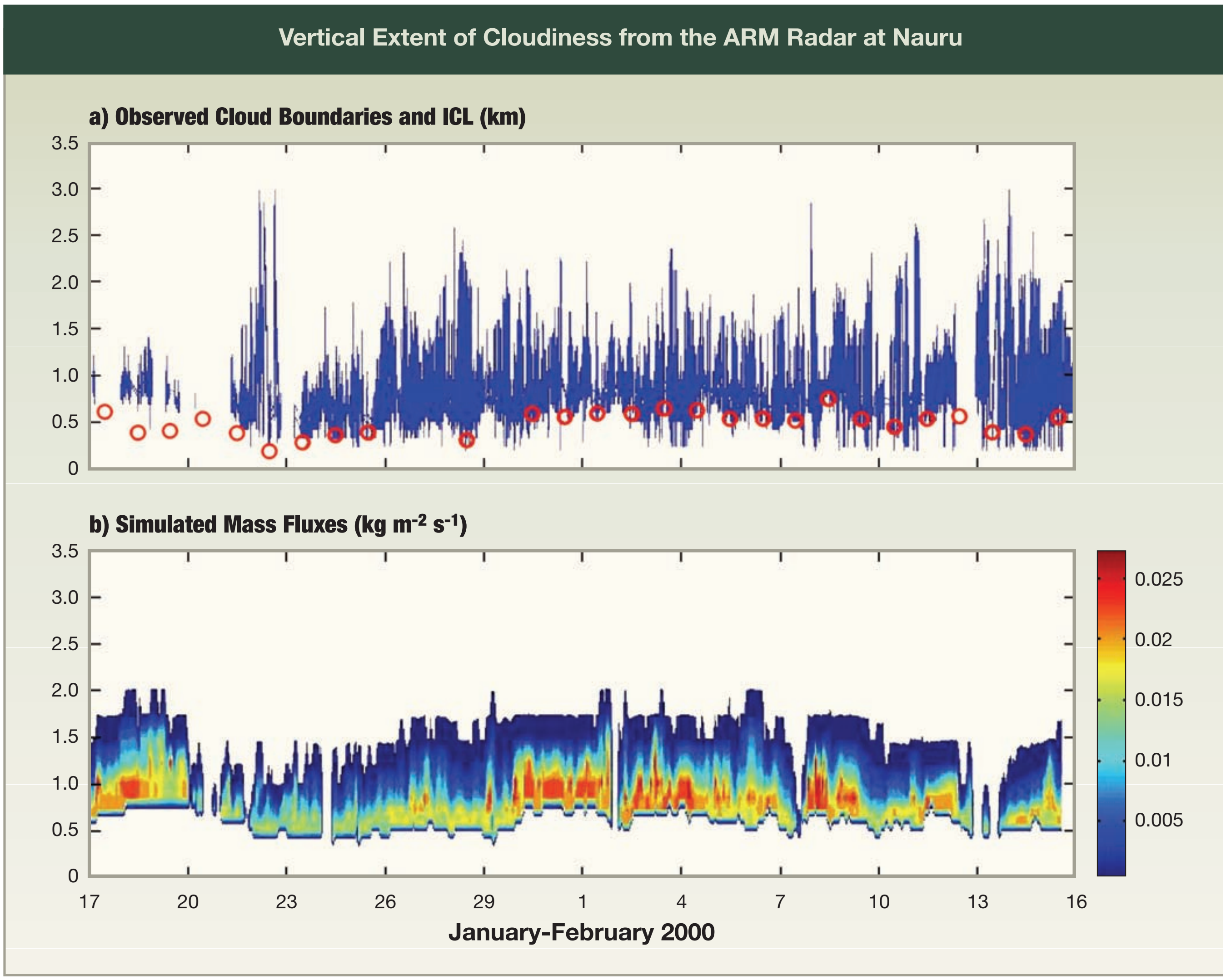


Figure 13: Vertical Extent of Cloudiness from the ARM Radar at Nauru. Time series of the vertical extent of cloudiness from the Atmospheric Radiation Measurement (ARM) radar at Nauru (top panel). Bottom panel shows the vertical distribution of the cumulus mass flux, which is an indicator of the vertical extent of the shallow cumulus clouds. *Credit: P. Zhu and C.S. Bretherton, University of Washington (reproduced from* **Monthly Weather Review** *with permission from the American Meteorological Society).*

the European Centre for Medium-Range Weather Forecasts (ECMWF) in simulating Arctic cloud systems. The two climate models were evaluated under the framework developed through a joint effort between DOE's Climate Change Prediction Program (CCPP) and the ARM program, the CCPP-ARM Parameterization Testbed, which is a diagnostic tool for evaluating climate models using weather prediction techniques. As revealed in the study, the models simulate the occurrence of clouds fairly well, but there are substantial errors in cloud microphysical properties. ARM data will be used to suggest improvements for these models (see Figure 14).

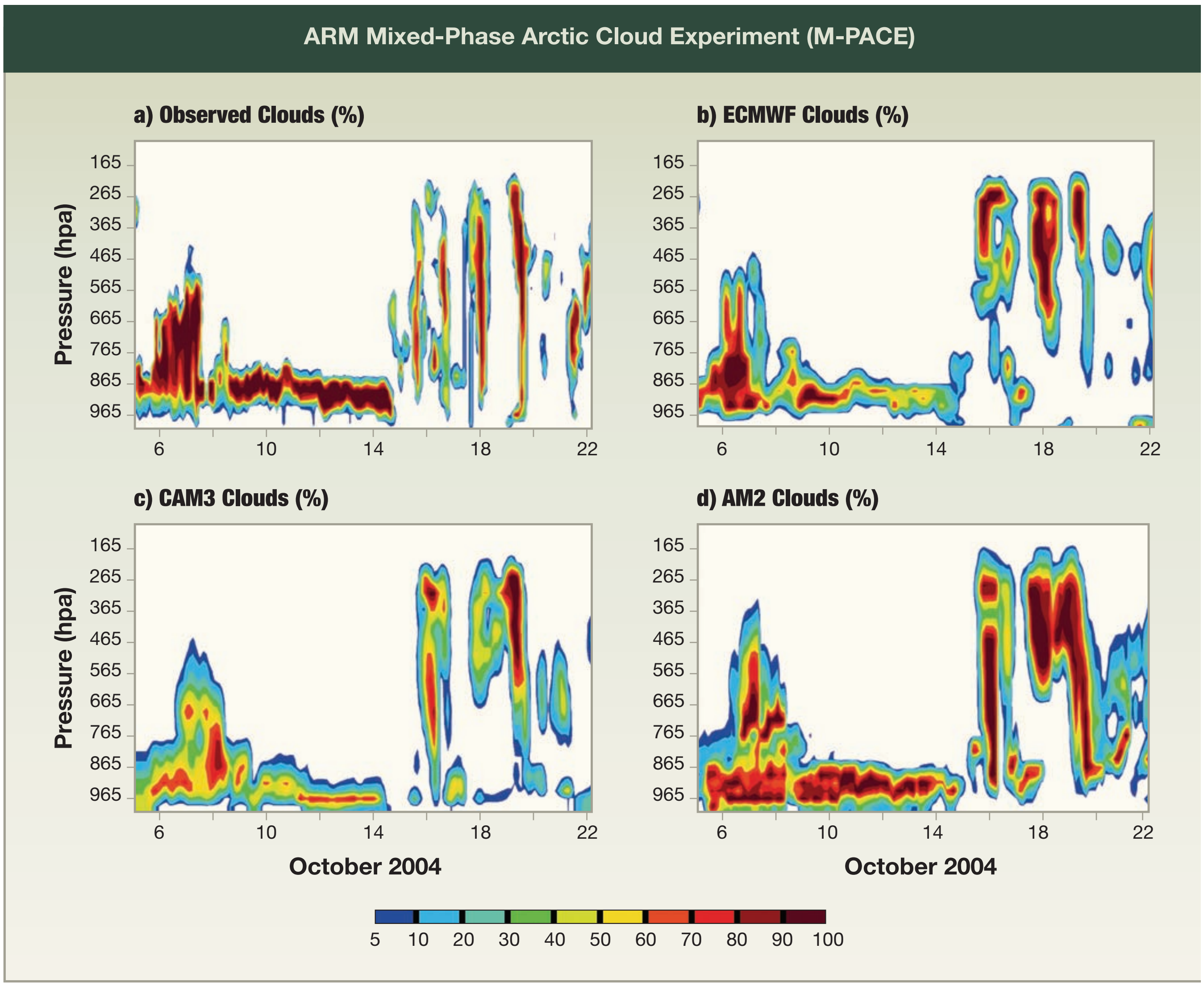
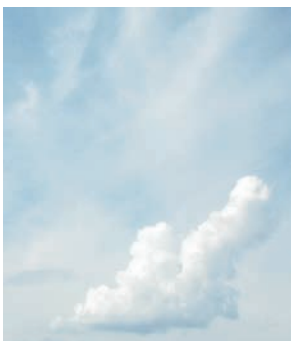


Figure 14: ARM Mixed-Phase Arctic Cloud Experiment (M-PACE). Temporal and vertical distribution of observed and simulated clouds from the European Centre for Medium-Range Weather Forecasts (ECMWF), CAM3, and AM2 at Barrow, Alaska, during the M-PACE periods. *Credit: S. Xie, Lawrence Livermore National Laboratory; S.A. Klein, Lawrence Livermore National Laboratory; J.J. Yio, Lawrence Livermore National Laboratory; A.C.M. Beljarrs, ECMWF; C.N. Long, Pacific Northwest National Laboratory; and M. Zhang, State University of New York, Stony Brook (reproduced from* **Journal of Geophysical Research** *with permission from the American Geophysical Union).*

New Model of Cloud Drop Distribution that Simulates Drop Clustering. CCSP scientists have developed size-dependent models of the spatial distribution of cloud drops that simulate the observed clustering of drops. Understanding of spatial distribution and small-scale fluctuations in cloud droplets is essential for both cloud physics and atmospheric radiation. For cloud physics, the coalescence growth of raindrops depends upon size distribution while, for radiation, the spatial distribution of cloud drops has a strong impact on cloud radiative properties. In contrast to currently used models that assume homogeneity and therefore a Poisson distribution of cloud drops, the new models show strong drop clustering, which increases with larger drop size. Clustering has vital consequences for rain physics, explaining how rain can form more quickly in the new models than simulations made with the former, homogenous models. The new models also help to explain why remotely sensed cloud drop size distributions are generally biased.



Improved Understanding and Modeling of Cloud Aerosol Interaction, Cloud Organization, and Radiative Properties.[17]

Studying Stratus, Radiation, Aerosol, and Drizzle. The DOE's ARM and Atmospheric Science Programs and the U.S. Office of Naval Research conducted a joint extensive field experiment at Pt. Reyes, California. The objectives were to collect data from cloud-aerosol interactions and to improve understanding of cloud organization that is often associated with patches of drizzle.

Simulating Radiative Properties of Ice Clouds. Scientists developed a model that provides a means of predicting the radiative properties of ice clouds in terms of explicit microphysical properties, such as the parameters describing a bimodal size distribution that accounts for the smallest ice crystals and the various ice crystal shapes in the size distribution. The ice radiative properties predicted by the model code are being used in a development version of the NCAR CAM/Community Climate System Model (CCSM), and it will be a candidate for inclusion in CAM4/CCSM4. The explicit coupling between ice particle microphysical properties and radiative properties also provides a better opportunity for investigating the role of aerosol-ice nucleation processes in global climate processes.

Percentage of Global Land Areas Affected by Serious Drought Increases.[2]
Global Palmer Drought Severity Index data and offline simulations with the NCAR land-surface model were used to study the potential drying over global land areas associated with the warming during the last several decades. This study found that the percentage of the global land area affected by serious drought more than doubled from about 15% during the 1970s to about 30% in the early 2000s. Widespread drying occurred over much of Europe and Asia, Canada, western and southern Africa, and eastern Australia. The warming-induced drying has occurred over most land areas with

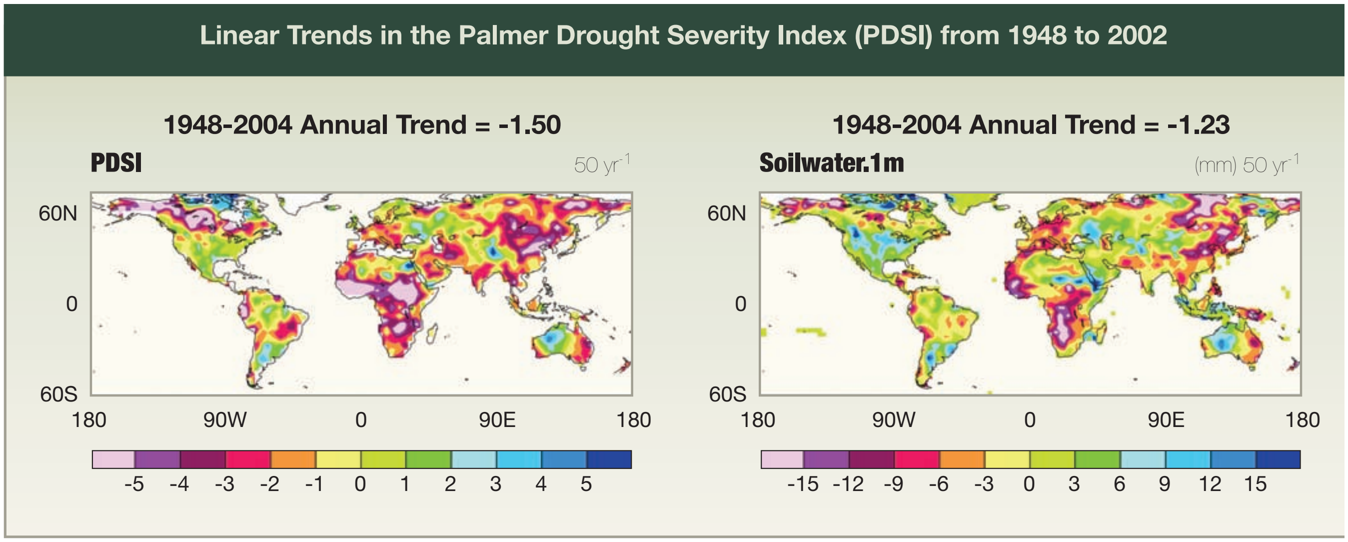


Figure 15: Linear Trends in the Palmer Drought Severity Index (PDSI) from 1948 to 2002. These data products show drying (reds and pinks) across much of Canada, Europe, Asia, and Africa and moistening (green) across the United States, Argentina, Scandinavia, and western Australia. *Credit: A. Dai, K.E. Trenberth, and T. Qian, National Center for Atmospheric Research (reproduced from* ***Journal of Hydrometeorology*** *with permission from the American Meteorological Society).*

the largest effects in northern mid- and high latitudes. In contrast, rainfall deficits alone were the main factor behind expansion of dry soils in Africa's Sahel and East Asia. Figure 15 illustrates these trends.

Mass Decrease in the Greenland Ice Sheet.[13,19,21] Greenland hosts the largest reservoir of freshwater in the Northern Hemisphere, and any substantial changes in the mass of its ice sheet will affect global sea level, the meridional overturning circulation of the ocean, and therefore the climate system. The Greenland glaciers cover an area of about 1.7 million km^2 (a little smaller than Mexico) and are up to 3-km thick in spots. In the first direct, comprehensive mass survey of the entire Greenland Ice Sheet, scientists using data from the NASA/German Aerospace Center Gravity Recovery and Climate Experiment (GRACE) measured a significant decrease in the mass of the Greenland ice cap resulting from a speeding up of the flow of Greenland glaciers and accelerated ice discharge. GRACE detected a volume reduction in the Greenland ice sheet of 162 ± 22 km^3 (39 ± 5.4 mi^3) per year between 2002 and 2005. This is higher than all previously published estimates, and represents a contribution of about 0.4 mm (0.016 in) per year to global

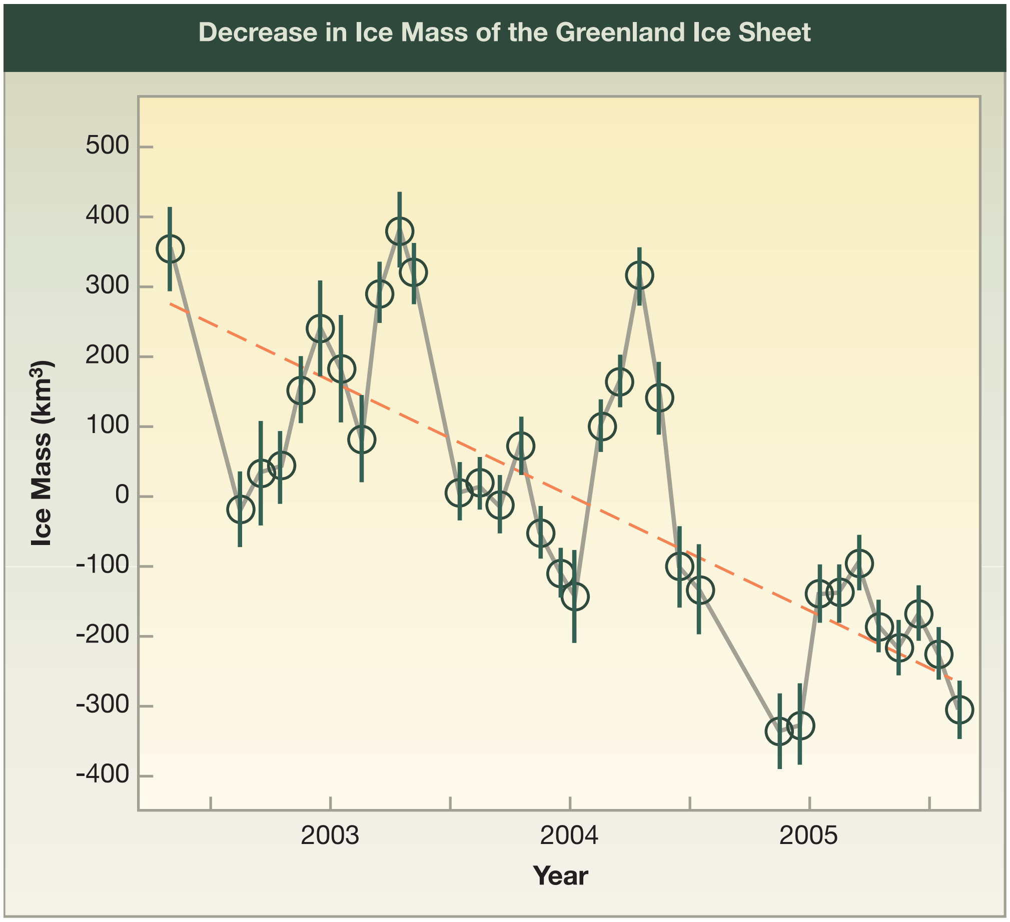
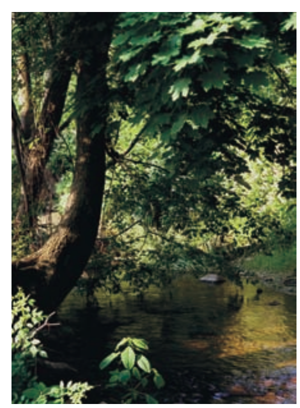


Figure 16: Decrease in Ice Mass of the Greenland Ice Sheet from mid-2002 to mid-2005. The rate of change over this period of GRACE monitoring represents a decrease of 162 ± 22 $km^3\ yr^{-1}$, which contributes about 0.4 ± 0.1 mm yr^{-1} to sea-level rise. *Credit: I. Velicogna and J. Wahr, University of Colorado (reproduced from* ***Geophysical Research Letters*** *with permission from the American Geophysical Union).*

sea-level rise as shown in Figure 16. The identical twin GRACE satellites track minute changes in Earth's gravity field resulting from regional changes in Earth's mass such as masses of ice, air, water, and solid earth that shift due to weather patterns, seasonal change, climate change, and even tectonic events. GRACE has the unique ability to measure monthly mass changes for an entire ice sheet—a breakthrough in our ability to monitor such changes.

Interannual Variability of the Hydrologic Cycle over North America.[1,5,6,22] Recent research findings indicate that dominant winter modes in the hydrologic cycle are due to moisture fluxes associated with extreme precipitation events over the west coast of the United States, and are controlled by strong El Niño Southern Oscillation (ENSO) events, such as those of 1982-1983 and 1997-1998 (El Niño) and 1989 (La Niña). In the central United States, moisture transport is associated with high-precipitation events and with moisture flux variability related to the droughts of 1983 and 1988. These research results are important because they point to a moisture storage component. The results have been incorporated in a new precipitation-recycling model that includes a soil moisture storage pool. The new recycling model was used to study the variability of monthly precipitation recycling over the conterminous United States from 1979 to 2000. Specific drought or flood years do not completely account for observed variability, pointing to a storage or "memory" term response, which subsequently affects interannual precipitation variability. To explore this soil moisture control, a novel method is being developed to use energy fluxes estimated from remote-sensing platforms to show that differences in energy fluxes (which drive moisture fluxes) are related to soil moisture through deep soil layer moisture effects on surface moisture fluxes. Deep soil influences on the uptake of moisture by plant roots result in high transpiration variability and changes in the overall energy balance. This potential vegetation response to a moisture storage pool plays a crucial role in land-atmosphere interactions through water transport in the form of evapotranspiration and root uptake, and carbon transport in the form of photosynthesis and respiration. Results show explicit correlations between vegetation variability, as controlled by topography, and the ENSO and North Pacific oceanic signals. Areas of vegetation variability found to be associated with the ENSO signal are uncommon to previous studies relating precipitation and temperature to ENSO, thus indicating a novel result and pointing to the hypothesized moisture "storage" memory. The focus of the initial phase of the analysis is on the continental United States to gain insight into general, wide-ranging relationships, yet focusing on particular ecological regions with greater vegetation variability. This will give further insight into influential mechanisms linking vegetation, climate, and physiography at small scales.



Changes in the Global Water/Energy Cycle Associated with Changes in the Carbon Cycle.[10] Afforestation is the process of converting open land into forest by planting trees or their seeds. It is generally considered beneficial for carbon sequestration (at certain time scales), ecosystem protection, soil moisture retention, reducing excessive surface runoff, improving replenishment of the groundwater table, and possibly increasing local precipitation by increasing surface boundary layer moisture convergence, among other benefits. However, these benefits need to be balanced against the adverse impacts that afforestation may have in certain regions, depending on local and regional climate conditions. In this particular study, a global analysis of 504 annual catchment observations showed that afforestation dramatically decreased streamflow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands, or croplands decreased streamflow by 180 mm yr^{-1} and 38% on average. After a slight initial increase in some cases, substantial annual decreases of 155 mm and 42% were observed on average for 6- to 10-year old plantations, and average losses for 10- to 20-year-old plantations were even greater (227 mm yr^{-1} and 52% of streamflow). Perhaps most important, 13% of the studied streams dried up completely for at least 1 year, with eucalyptus more likely to dry up streams than pines. Afforestation in drier regions (<1000 mm mean annual rainfall) was more likely to eliminate stream flow completely than in wetter regions. Mean annual renewable freshwater (percentage of annual precipitation lost as runoff) decreased about 20% with afforestation. For many nations whose total annual renewable freshwater is less than 30% of precipitation, afforestation is likely to have large impacts on water resources. These results suggest that afforestation and carbon cycle issues such as carbon sequestration need to be viewed together with their interfaces with the water cycle.

Evidence for Positive Trends in Moisture Recycling at High Northern Latitudes Leading to Vegetation Increases.[3,4] Most observational indicators of global climate change have been found directly in the temperature record or in physical and ecological processes that respond to changing temperature. Researchers used a tracer approach to examine the atmospheric branch of the hydrologic cycle by following the moisture in global rainfall back to its evaporative sources over the last 25 years. Along with the first detailed analysis and climatology of the global atmospheric water cycle, their study shows evidence of trends in recycling at high northern latitudes driven by changes in circulation as well as surface temperature. These trends are consistent with observed vegetation-related changes and most evident where the density of meteorological data influencing the atmospheric analyses is high (see Figure 17).

New Land-Surface Schemes in Climate Models that Include Photosynthesis Show Improved Climate Simulations of Water-Cycle Parameters.[8] A new physiology-based model of canopy stomatal conductance and photosynthesis was included in the latest version of the Goddard Institute for Space Studies (GISS) general circulation model (GCM), Model E1. The sub-model includes responses to atmospheric humidity and CO_2 concentration, which were missing from previous GISS GCM land-surface schemes. Measurements of moisture, energy, and CO_2 fluxes over four vegetation types were used to test and calibrate the sub-model. Photosynthetic leaf nitrogen was calibrated for each vegetation type from flux measurements. The new sub-model resulted in surface cooling over many regions that were too warm in previous simulations. Some warm biases of over 2°C cooled by more than 0.5°C, including over central Eurasia, South America, the western United States, and Australia. Some regions that were previously too cool warmed, such as the Tibetan plateau. A number of precipitation biases were reduced, particularly over South America (by up to 1 mm day^{-1}) and the oceanic

Spring Trends in Recycling Ratio from 1979 to 2003

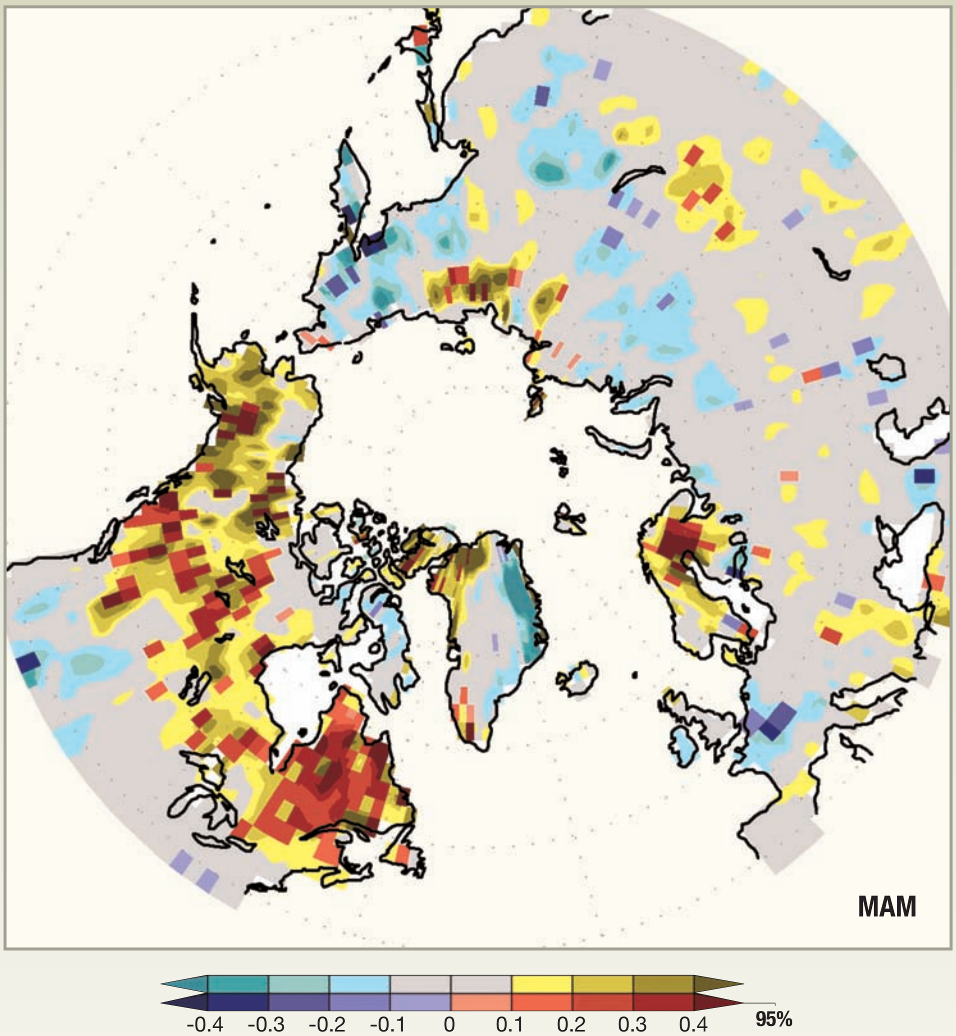


Figure 17: Spring Trends in Recycling Ratio from 1979 to 2003 over the High Latitudes of the Northern Hemisphere. Red and blue shades indicate regions of statistically significant trends with a confidence level of 95%. Positive trends dominate over North America, with especially strong and widespread trends over Canada and Alaska. There are also strong positive trends over Scandinavia during spring and over Britain and much of north-central Europe during fall (not shown here). Trends are generally weaker and not as widespread over Asia, where *in situ* meteorological observations are much less dense. *Credit: P.A. Dirmeyer and K.L. Brubaker, Center for Ocean-Land-Atmosphere Studies and the University of Maryland (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

inter-tropical convergence zone (by ± 1 mm day^{-1}), while coastal West Africa became significantly wetter. Cloud cover increased over many land areas previously too clear. Higher absolute canopy conductances and positive feedbacks with atmospheric humidity were largely responsible for the simulated vegetation influence on the atmosphere. High-latitude climate changes through the remote effects of increased tropical latent heating (heat released by precipitating clouds) resulted directly from improved characterization of tropical forest canopy conductance. The realistic representation of stomatal control of land evaporation and evapotranspiration is critical for the accurate simulation of atmospheric dynamics in climate models. Figure 18 shows seasonal maps of mean precipitation bias.

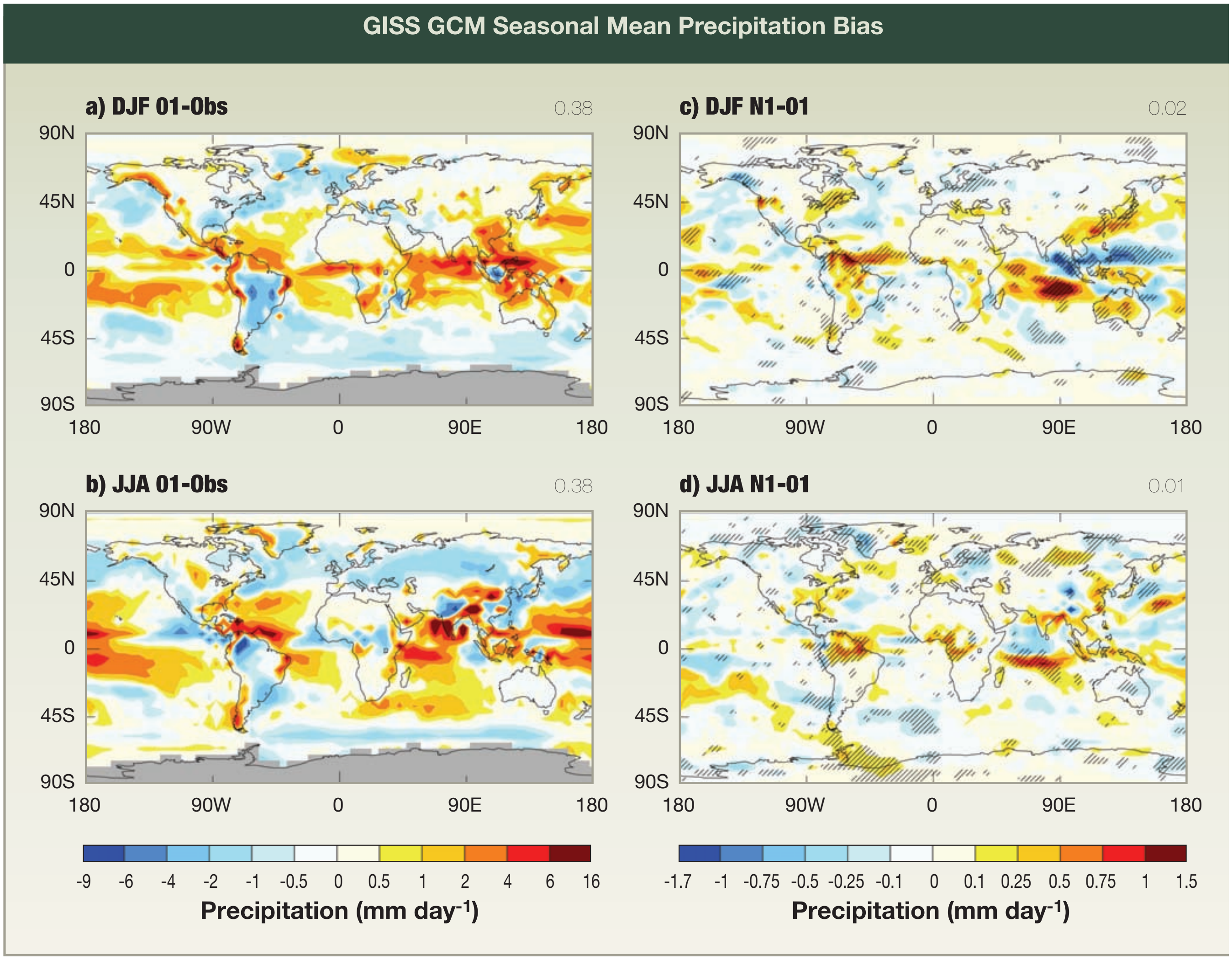


Figure 18: GISS GCM Seasonal Mean Precipitation Bias. These products generated using the RA97 canopy stomatal conductance sub-model in (a) DJF (-7.1 to +9.3 mm day^{-1}) and (b) JJA (-8.7 to +15.9 mm day^{-1}), and change due to new conductance sub-model in (c) DJF (-1.4 to +1.5 mm day^{-1}) and (d) JJA (-1.7 to +1.1 mm day^{-1}). Observations over land from New *et al*. (1999) and over oceans from Huffman and Bolvin (2005). Global means at upper-right corners. Hatched areas are significant at the 95% confidence level for a paired *t* test. *Credit: A.D. Friend, Laboratoire des Sciences du Climat et de l'Environnement; and and N.Y. Kiang, Columbia University (reproduced from* **Journal of Climate** *with permission from the American Meteorological Society).*

Correspondence between Observations and Streamflow Simulations by Climate Models, and Future Streamflow Projections.[16] CCSP scientists analyzed the long-term streamflow characteristics in an ensemble of recent climate simulations and projections by 12 different global climate models. They found encouraging correspondences between observed historical and simulated patterns of 20th-century regional streamflow variations on multi-decadal time scales. The same models project 10 to 40% increases in runoff in eastern equatorial Africa, the La Plata basin, and high-latitude America and Eurasia, and 10 to 30% decreases in southern

Africa, southern Europe, the Middle East, and mid-latitude western North America by 2050 under a mid-range scenario of greenhouse gas emissions leading to an atmospheric CO_2 concentration of approximately 530 ppm by the mid-21st-century.

Linking the Time Scales and Amplitudes of Groundwater and Surface Water Flows to Global Climate Variations.[9] The time scales and amplitude of the hydrologic responses to climate variations depend on the time scales and mechanisms of the climate forcings, on how closely the groundwater and surface water systems are coupled to each other and to climate variations, and whether the overall hydrologic responses in a given setting depend more on slower aquifer responses or more rapid streamflow responses. An innovative study used a global GCM (ECHAM-T42) coupled to a regional groundwater model (RGWM) of the Santa Clara-Calleguas Basin to examine the simulated precipitation rates from the GCM for the period 1950 to 1993. The study found that interannual to interdecadal time scales of ENSO and Pacific Decadal Oscillation climate variations are imparted to the simulated climate-driven recharge (and discharge) variations. For example, the simulated response of average groundwater level to ENSO variations at a key observation well in the basin is 1.2 m per °C compared to 0.9 m per °C in the observations. This close agreement shows that the GCM-RGWM combination can translate global-scale climate variations into realistic groundwater responses. Figure 19 illustrates the spatial relationships and groundwater budgets of components of the water resource extraction and distribution systems for the Santa Clara-Calleguas Basin.

The Groundwater Connection in the Amplification of Seasonal- to Century-scale Oscillations in Closed Basins.[7,20] A recent study shows that the space-time components of runoff have a complex relationship with orography, where the balance of precipitation and evapotranspiration interacts with the mountain-front watershed to filter and amplify runoff to the Great Salt Lake. The study examined the space-time patterns of annual, interannual, and decadal components of precipitation, temperature, and runoff using long-record time series across the steep topographic gradient of the Wasatch Front in northern Utah. This region forms the

Water Resource Extraction and Distribution System

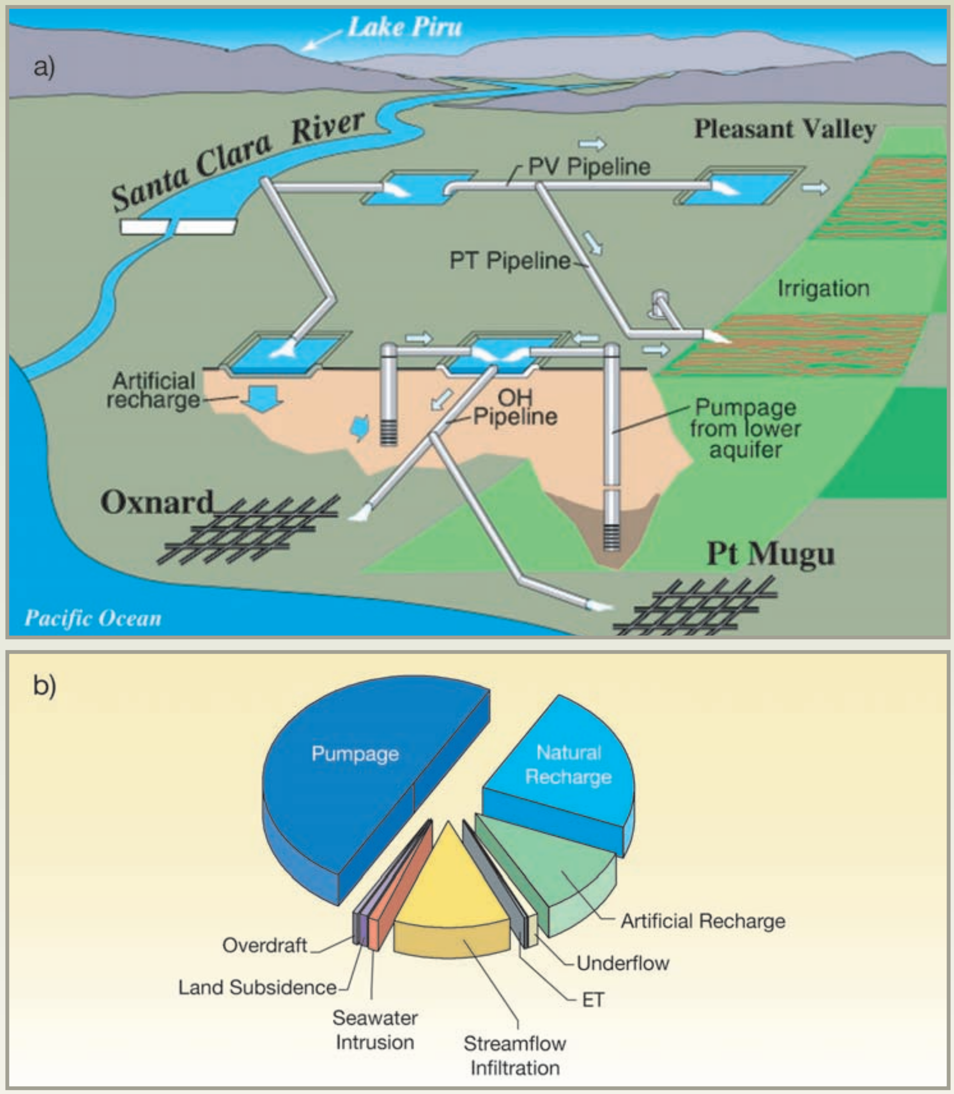


Figure 19: Water Resource Extraction and Distribution System. (a) Diagram showing components of water resource extraction and distribution system; and (b) generalized groundwater budget for the Santa Clara-Calleguas Basin, Ventura County, California. *Credit: R.T. Hanson and M.D. Dettinger, University of California at San Diego.*

major drainage area to the Great Salt Lake. The approach used multi-channel singular spectrum analysis as a means of detecting dominant oscillations and spatial patterns in the data (see Figure 20 for a depiction of the spatial patterns). Results showed that high-elevation runoff is dominated by the annual and seasonal harmonics, while low-elevation runoff exhibits strong interannual to decadal oscillations. In particular, significant low-frequency components are found at intermediate and low elevations of the Wasatch Range. The research suggests that these results are due to mountain-front hydrologic conditions supporting groundwater storage and base flow. The transmission

Wetting and Drying Phases of the Great Salt Lake

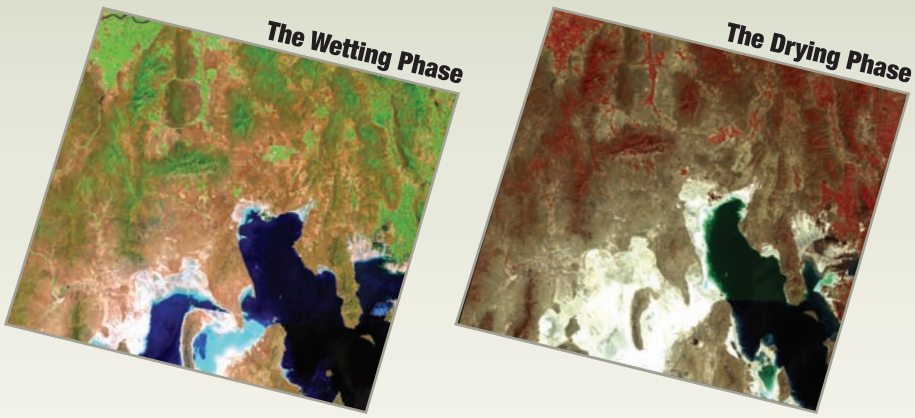
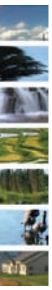


Figure 20: Wetting and Drying Phases of the Great Salt Lake. *Credit: C. Duffy, Pennsylvania State University and USGS for the original Landsat imagery.*

zone, or the zone of streamflow loss to groundwater, was identified as affecting annual, interannual, and decadal runoff components. Overall, the groundwater-streamflow relation represents a "low-pass" filter for the precipitation/evaporation input signal. The filtering effect is likely to be proportional to the scale of volumetric groundwater storage in the mountain blocks and basin sediments.

Collaborative Research: Development of Informatics Infrastructure for Hydrologic Sciences.[14] Scientists associated with the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI) have developed a Hydrologic Information System (HIS) that combines point data (on-site measurements), spatial data (GIS-based geographical data), remotely sensed (satellite) data, and meteorological data. HIS provides a "digital watershed" with access through a common portal to a wide variety of hydrologic and water quality data collected by many agencies, and with a "translator" that makes seamless connections. HIS will later be expanded to provide hydrologic representations and analyses. With this hydrologic digital library, users can find desired items through web-based searches and acquire them through automated data acquisition systems. The goal is to allow the scientific community and resource managers to access information needed to define fluxes and flow paths, residence times, and mass balances—key elements for testing hydrologic hypotheses. HIS provides data fusion for mating and communication among different formats to form a coherent framework in space and time.



HIGHLIGHTS OF PLANS FOR FY 2007

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 predictive model development; and applications to decision-support systems. A fundamental objective of the program is to ensure that observational capability is enhanced and improved, and that the data assimilation and modeling/prediction systems are more reliable and accurate at the point of application. Several promising results from recent research will be further explored with an aim to transfer this knowledge to operational applications that provide societal benefit. 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. Several scientific questions remain, ranging from warnings of natural hazards to the impact of global climate change, be it from natural or anthropogenic causes. The program outlined for FY 2007 will lead to improvements in planning, decisionmaking, and resource management activities—a major aim of the program. However, significant unresolved research issues will require longer term efforts. To address these research and applications needs, several initiatives will be launched in FY 2007. Following are selected highlights of FY 2007 activities.

Integration of Water Cycle Observations, Research, and Modeling: A Prototype Project. Following CCSP guidelines, an interagency "integrating" priority project will be implemented (contingent on funds) as the first of similar activities that are envisaged under the water cycle element over the next decade. The purpose of this project is to address significant uncertainties associated with the water cycle through a study that comprehensively addresses the water budget within a limited spatial and temporal domain. This FY 2007 prototype project will integrate information describing the state, fluxes, and variability associated with and across hydrologic regimes. To accomplish this FY 2007 near-term priority, a number of agencies are planning to contribute to DOE's planned field campaign (CLASIC) at the ARM Southern Great Plains site. The multi-agency effort will include space-based observations, aircraft campaigns, surface and subsurface hydrologic components, isotopic measurements, CO_2 fluxes, research-mode modeling, and applications to decision-support systems as a first integrated, interagency attempt to build the science and applications components required to begin to "close" the water budget within a limited area.

This activity will address CCSP Goals 1, 2, 3, and 5
and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Participation in the Convective and Orographically Induced Precipitation Study. The ARM Mobile Facility (AMF) will participate in the international Convective and Orographically Induced Precipitation Study in the Black Forest area in summer 2007. The goal is to identify the reasons for deficiencies in the quantitative precipitation forecast and to improve the skill of mesoscale model forecasts with respect to precipitation. The primary goal of the ARM program is to improve the treatment of cloud and radiation physics in global climate models in order to improve the climate simulation capabilities of these models. These efforts have been enhanced by the addition of the AMF to study cloud and radiation processes in multiple climatic regimes. The AMF can be deployed to sites around the world for durations of 6 to 18 months. Data streams produced will be available to the atmospheric community for use in testing and improving parameterizations in global climate models.

This activity will address CCSP Goals 1, 2, and 3
and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

The Cloud and Land Surface Interaction Campaign. The Cloud and Land Surface Interaction Campaign (CLASIC), a field campaign proposed by DOE for implementation in FY 2007, will focus on interactions between the land surface and the early cumulus life cycle, especially the stages leading from cumulus humilis to cumulus congestus. It will cover a period of 1 to 3 months and will straddle the winter wheat harvest when large changes in the land surface lead to large changes in surface albedo, latent heat flux, and sensible heat flux. By DOE's invitation, CLASIC will be developed further as an integrated, interagency project, contingent on FY 2007 funding and on expressions of multi-agency interest (see next item).

This activity will address CCSP Goals 1, 2, 3, 4, and 5
and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Blueprint for an Integrated Observing Platform: Bedrock to Boundary Layer and Beyond. The Science Steering Group (SSG) for the CCSP water cycle element will develop a blueprint for a hypothetical integrated observing platform that would be capable of quantifying all aspects of the terrestrial water and energy cycle. The plan will be conceptual but with sufficient specific detail so that one or more aspects of the platform could be implemented during one or more of the integrated

interagency projects that the water cycle element may carry out over the next decade of research and applications. The blueprint could also serve as a basis for deploying terrestrial hydrologic observatories, and be used for the planning of field campaigns. The conceptual plan will include observational requirements that derive from needs for improved models of the water cycle, improved water cycle process parameterization schemes, scale interactions, and improved characterization and modeling of fluxes and transports in the atmosphere, land surface (including vegetation, streams, and reservoirs), subsurface (including the water table and subterranean aquifers), and coastal zones. The inclusion of remote-sensing and *in situ* instruments, fixed and portable, are envisaged. Existing observing systems will form the substrate for the integrated observing platform to which innovative technological capabilities and designs will be added. The plan will make the case for the need for new and improved observational and modeling capability to address known scientific challenges facing both water cycle research and applications to the management of water resources (quantity and quality).

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Integration of Space-Based Observations and Land Surface/Hydrology Data Assimilation Systems. The GRACE satellite has demonstrated that large-scale changes in the integrated column water content of the combined atmosphere, land surface (including rivers and reservoirs), soil moisture, and groundwater system compares well with the changes documented by the Global Land Data Assimilation System. Investigations in FY 2007 will further explore whether GRACE data can be assimilated by and/or provide integral closure constraints for the Land Information System (LIS) to improve the water/energy cycle research and applications analysis products generated by these systems. This will be done alongside data assimilation work to incorporate other satellite data products (e.g., soil moisture, snow cover area and water equivalent, and surface temperature) into LIS.

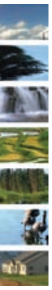
This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

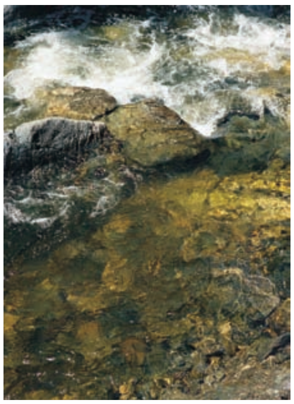
Advanced Ensemble Multi-Model Prediction Techniques for Surface and Subsurface Hydrologic Parameters. Expanded efforts will be made to calibrate and validate research-mode ensemble (multi-model) forecasting techniques for surface and subsurface hydrologic parameters, especially at longer seasonal time scales. The objective is to transfer the improved hydrologic prediction techniques to operational applications at seasonal and interannual time scales. This activity will expand on the recently developed Advanced Hydrological Prediction Service (AHPS) of NOAA's hydrologic forecasting system that includes new model calibration strategies, distributed modeling approaches, ensemble forecasting, data assimilation techniques, enhanced data analysis procedures, flood forecast inundation maps, hydrologic routing models, and multi-sensor precipitation estimates. Data from USGS stream flow observations and gridded multi-sensor precipitation and snow-water equivalent estimates, among other data, will also be transferred into the AHPS data assimilation system. New approaches for remotely sensing precipitation, snow, and other inputs will be integrated into the hydrologic forecast operation. AHPS is slated to be fully implemented nationwide in 2013. In parallel, CCSP researchers will participate in the further development of an international project, the Hydrological Ensemble Prediction Experiment. This project will bring the international hydrological community together with the meteorological community and demonstrate how to produce reliable hydrologic ensemble forecasts that the emergency management and water resources sectors can use with confidence to make decisions that have important consequences for the economy and for public health and safety.

This activity will address CCSP Goals 1, 3, 4, and 5 and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

A New Strategy for Improving Water/Energy Cycle Components in Earth/Climate System Models. Integrated Earth/climate system modeling efforts, combining the water/energy cycle and other components of the climate system, will be actively pursued in FY 2007 and beyond. In particular, recent observations, diagnostic studies, and research analyses have demonstrated the need to incorporate certain elements in weather forecast and climate (variability) prediction models operating at various time scales. For short-term forecasting (e.g., 5 to 10 days), these elements include the diurnal cycle, coupling between the atmosphere and the ocean (mixed layer down to the thermocline at a minimum), and the coupling of the land surface (including vegetation) and subsurface hydrology (down to the water table at a minimum) to the atmosphere. For climate variability predictions (e.g., monthly to seasonal and beyond), these elements include the dynamics of the interaction between the ocean mixed layer and the deeper mid-ocean, the dynamics of interactions between the land and the water table, and dynamic vegetation changes. These components have a direct impact on the interaction and exchange fluxes of water, energy, heat, and momentum at the interfaces between the atmosphere and the land surface/vegetation or the oceans. For longer climate change time scales, fully coupled models of the atmosphere-land and hydrosphere/biosphere-ocean-cryosphere are required. The key issue is how to observe and model coupling processes. To support this activity, improved observing systems are also required. This effort is considered central to CCSP, and the global water cycle element plans to pursue this activity jointly with other CCSP program elements. This integrating activity will be initiated in FY 2007, but implementation is expected to take the better part of a decade for improvements in the system of combined observations, modeling, prediction, and applications.

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.





Science Plans for the Extension of the Global Energy and Water Experiment (GEWEX)-Coordinated Enhanced Observing Period (CEOP) through 2010. The initial successes of CEOP have led its Science Steering Committee and its Advisory and Oversight Committee to endorse plans for a second phase of CEOP that will extend to the end of 2010. This decision, which CCSP global water cycle scientists are closely involved with, has also been supported by the broader World Climate Research Programme (WCRP) community. The WCRP Joint Scientific Committee (JSC) has taken steps to help develop the unique attributes of CEOP's observation and data component by providing guidance through the WCRP Observations and Assimilation Panel. In a similar manner, the JSC plans to ensure that the CEOP science focus remains closely integrated with and complementary to the overall objectives of GEWEX and the other core projects of WCRP. In this manner, CEOP will continue to evolve as a leading contributor to water and energy cycle studies in the global climate research community and remain a fully functioning integrative component of the WCRP. CCSP researchers will contribute to CEOP in developing the Phase 2 Implementation/Science Plan.

This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

New Watershed Climate Assessment Decision-Support Capabilities. Climate change presents a range of risks and opportunities to water managers. To minimize risk and take advantage of opportunities, tools are necessary to promote adaptive and forward-looking environmental management by decisionmakers at all levels. Several projects have been initiated in the area of decision support. A new climate assessment capability, the Better Assessment Science Integrating Point and Non-point Sources (BASINS) watershed modeling system, is being developed. BASINS combines data and models from agencies including EPA, USDA, and USGS in a single system. The new tool will facilitate assessment of the influence of climate variability and change—together with land-use change and other stressors—on water quantity and quality. The tool will also provide the capacity to evaluate potential adaptation strategies to increase the resilience of water systems to changes in climate.

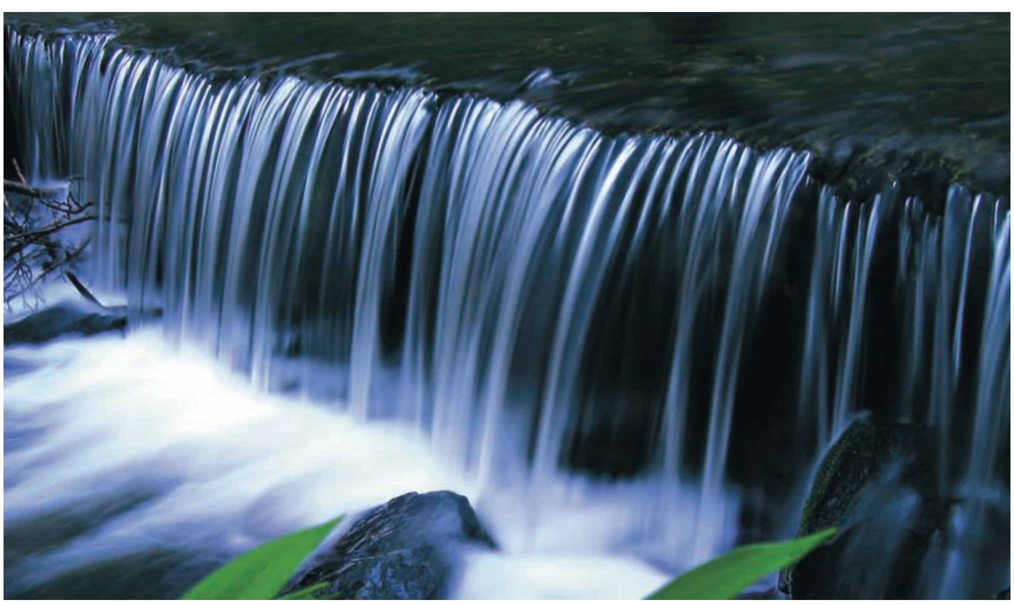
This activity will address CCSP Goals 4 and 5 and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

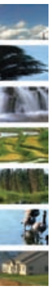
New Tools for the Assimilation of Remote-Sensing Data into Distributed Water Quality and Sediment Transport and Erosion Models. The research activities of the USDA Agricultural Research Service (ARS) in the area of land data assimilation systems and model analysis are focused on the efficient integration of ground-based and remote-sensing data into critical resource and conservation practice assessment models. Existing agency research projects are aimed at the sequential assimilation of surface soil moisture retrievals and vegetation indices from microwave and visible remote sensors to constrain crop growth and root-zone water balance models. Future work will expand this emphasis to include the assimilation of remote-sensing data into distributed water quality and sediment transport and erosion models. Particular emphasis will be paid to developing data assimilation and modeling capabilities to quantify benefits arising from the adoption of conservation practices within agricultural watersheds.

This activity will address CCSP Goals 4 and 5
and Questions 5.4 and 5.5 of the CCSP Strategic Plan.

Tools to Help Develop "Best Management Practices" to Lessen the Impacts of Climate Variability and Change. Similar to BASINS, a decision-support capability is being developed with models from EPA and the ARS Water Erosion Prediction Project soil erosion model. The new climate assessment capability will enable land managers to develop best management practices to lessen the impacts of climate variability and change on sediment loading to streams.

This activity will address CCSP Goals 4 and 5
and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

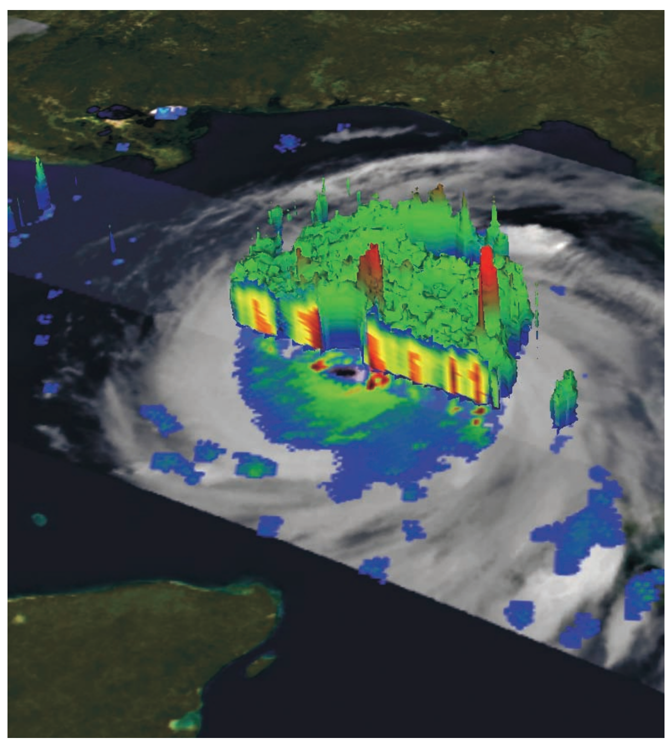




Integration of Information on the Effects of Changing Precipitation Patterns into Infrastructure Planning Processes. Communities around the United States are investing billions of dollars on upgrading combined sewer systems to comply with new regulations for combined sewer overflows. Previous work has suggested that climate change could alter the effectiveness of existing long-term control plans. Work has been initiated with local utility managers to better integrate information on the effects of changing precipitation patterns into infrastructure planning processes using decision-support tools such as those models developed by EPA in collaboration with other agencies.

This activity will address CCSP Goals 4 and 5 and Questions 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Initial Analysis and Calibration/Validation of Observations from the CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Research Satellites. Researchers plan to use new observations from CloudSat and CALIPSO, launched in mid-FY 2006, to measure the vertical structure of clouds and aerosols and to improve understanding of their radiative properties. The data will also provide vital information on global and regional pollution transport and its direct and indirect effects on cloud and precipitation processes, of which the latter are much more difficult to quantify. The data will complement existing satellite observations from Terra, Aqua, Aura, and Tropical Rainfall Measuring Mission (TRMM) as well as surface-based observations from ARM and the Baseline Surface Radiation Network, among others. As possible, and contingent on FY 2007 funding, these data will be utilized, in research mode, in the interagency integrated field campaign proposed as an interagency expansion of CLASIC.



This activity will address CCSP Goals 1, 2, and 3 and Questions 5.1, 5.2, and 5.3 of the CCSP Strategic Plan.

Combined Management of Groundwater and Surface Water Resources. Recent experimental research shows that coupling global GCMs with regional groundwater and surface water models have predictive capabilities that exceed the capabilities of the individual component models, especially at time scales that are important to water resource management. These early research findings will be tested further with the objectives of improving the combined water resources prediction system and transferring these research results into information that supports the operational decisionmaking infrastructure and decision-support systems. This new concept will be integrated into the implementation strategy of the global water cycle component over the next decade. Early testing will be attempted during one or more of the interagency integrated projects currently being planned for the next several years of the program. Further calibration will also allow for improved assessments of the impacts of projected global climate change at regional and local spatial scales.

This activity will address CCSP Goals 1, 2, 3, 4, and 5 and Questions 5.1, 5.2, 5.3, 5.4, and 5.5 of the CCSP Strategic Plan.

Research on Extended Drought: Causes, Monitoring, Analysis, Prediction, and Support for Drought Information Systems. Extended droughts have large impacts on water resources, agriculture, the energy industry, and natural ecosystems, among others. The global water cycle element places considerable importance on research into the causes of extended droughts and their prediction or early warning through several, if not all, of the activities identified previously. The activities include the need for better observing and monitoring systems (surface- and space-based), cloud and precipitation process studies, improved coupled modeling and prediction systems, and integrated data and information delivery systems. Major scientific issues also need to be resolved regarding the response of the continental water cycle to projected global warming, including how soil moisture balance will affect evaporation in response to greater energy availability at the land surface; how warming will influence the partitioning of water at the land surface between surface runoff and groundwater recharge; and how likely vegetation is to respond to changes in the timing and rates of water and energy supplies to the

atmosphere-land surface interface. This new activity is aimed specifically at a better understanding and prediction of droughts and the processes that cause them, which cut across many temporal and spatial scales ranging from seasonal to interannual to decadal, and from regional to continental. Moreover, as a renewed effort in FY 2007 and beyond, plans are being developed to incorporate enhanced information through-flow from research to experimental analysis and prediction systems to applications that supply the data needed by planning and decisionmaking infrastructures. This activity will be carried out jointly with other CCSP interagency working groups such as Climate Variability and Change, Land-Use and Land-Cover Change, Ecosystems, Carbon Cycle and particularly Decision Support and Human Contributions and Responses, thereby contributing to the recently established National Integrated Drought Information System.

This activity will address CCSP Goals 1, 4, and 5 and Questions 5.4 and 5.5 of the CCSP Strategic Plan.

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