NASA Research Strategy for Earth System Science: Climate Component

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ABSTRACT

This paper describes the principles adopted by the NASA Earth Science Enterprise in formulating a comprehensive 2002–2010 research strategy for earth system science, and outlines one component of this broad interdisciplinary program, focused on physical climate research. Before embarking upon topical discussions of each element of the program, the authors sketch NASA's overall strategy for climate research and organize the main research thrusts according to a logical progression from documenting climate variability and trends in relevant climate forcing factors, to the investigation of key climate responses and feedback mechanisms, consequences for weather and water resources, and climate prediction issues. The ultimate challenge for NASA's earth system science program, a major contribution to the U.S. Global Change Research Program, is to consolidate scientific findings in the different disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land, and biosphere system. The hallmark of NASA programs is indeed the integration of observations, principally global observation from research and operational satellite and surface-based observation networks, into consistent global datasets to support its scientific research programs and the verification of earth system model predictions against observed phenomena.

1. Introduction

As part of its strategic plan, the National Aeronautics and Space Administration (NASA) formulated the goal of "utilizing the knowledge of the Sun, Earth and other planetary bodies to develop predictive environmental, climate, and natural resource models to help ensure sustainable development, and improve the quality of life on Earth" (NASA 1998). We know now that, over geologic periods, the earth climate is governed by the interplay of two major cycles: the cycling of carbon through the earth atmosphere, terrestrial vegetation, oceans, sediments, and lithosphere, and the cycling of water through the atmosphere, rivers, and oceans. The recognition of multiple linkages between the earth's physical environment and the biosphere is a discovery of the twentieth century, which led to the new concept of *earth system science*. This new scientific paradigm is founded on the notion that the global earth environment can be understood only as an interactive system embracing the atmosphere, oceans, and sea ice, glaciers, and ice-sheets, as well as marine and terrestrial ecosystems. The NASA Earth Science Enterprise (ESE) aims to obtain a scientific understanding of the entire earth system, on a global scale, by describing how the system's component parts evolve, how they function and interact, and how they may be expected to change in the future.

In its report Global Change Research Pathways for the Next Decade (NRC 1999), the National Research Council (NRC) highlighted the complexity of earth system science and the multiplicity of interactions between component processes. In drafting this scientific strategy for the U.S. Global Change Research Program (USGCRP), the NRC identified a wide range of unsolved scientific questions, but also emphasized the need for a focused plan, concentrating research efforts and resources on critical scientific problems that are most relevant to economy and national policy

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issues. NASA's earth science program is one of the major components of the Global Change Research Program (USGCRP 2000). NASA defined the objectives of its program by formulating a set of overarching scientific questions (Table 1) that reflect the priorities highlighted by the NRC and also the nature of NASA's specific contributions to interdisciplinary earth system science research. NASA's contribution includes a unique combination of research capabilities: space-based global observing systems and long-range airborne observing facilities, integrated global data analysis and modeling programs, and the ability to facilitate the development of applications to practical problems in food and fiber production, water and natural resource management, natural hazard reduction, and other environment-dependent activities.

The scientific questions formulated by NASA can be envisioned as successive steps in a logical progression from observation and scientific understanding to prediction:

- How is the global earth system changing?
- What are the primary forcings of the earth system?
- How does the earth system respond to natural and human-induced changes?
- What are the significant consequences of global change for human civilization?
- What changes in the earth system will take place in the future?

This conceptual approach applies in principle to any aspect of earth system science, but it is particularly relevant to the study of climate and climatic change. The present paper focuses on two components of the ESE's research strategy, the study of the global water and energy cycle, and the role of oceans and ice in the climate system, addressing specifically the questions italicized in Table 1. The other components of this interdisciplinary strategy—atmospheric chemistry and its relation to climate, ecosystem and carbon cycle research, solid earth science—will be addressed elsewhere.

Information for global change research comes from a multiplicity of national and international sources, including research and operational satellite programs, as well as surface-based observations carried out by research institutions and government agencies. The ESE seeks the cooperation of these national and foreign partners to maximize returns from its own scientific investments. In particular, the ESE actively cooperates with operational environmental agencies in the United States and abroad to ensure the long-term continuity of key environmental measurements, and participates in related applied research programs such as the U.S. Weather Research Program. Relevance to operational needs or commercial applications is important for NASA, since such applications imply a potential for cooperation with responsible federal, state, and local government agencies. The ESE has initiated a focused applications program to facilitate relevant applied research activities and application demonstration projects through partnership with these government agencies and the private sector. Consistent with its mission as a research and technology agency, NASA is attentive to opportunities to enhance space, airborne, or ground-based technologies that may be applied to its scientific research efforts. The ESE technology development program and its linkages to the research strategy are described in the ESE Technology Plan.

2. A strategy for climate research

What do we need to know about climate change? Basically, climate science questions can be boiled down to three fundamental (and distinct) issues:

- The existence—or absence—of significant variations or trends in climate and the global water cycle, and the extent to which these changes are consistent with observed trends in climate forcings and current understanding of climate response processes.
- The extent to which variations in global climate (current or predicted) induce predictable changes in the frequency, intensity, and geographic distribution of weather systems that generate winds and rain, control the replenishment of freshwater resources, and, generally, govern mean fluxes of water and energy that drive all components of the global earth system.
- What climate surprises may be in store for the future, such as extensive melting of Arctic sea ice, weakening of the overturning circulation of the Atlantic Ocean and associated heat transport, surging of Antarctic ice streams, and accelerated mass loss from polar ice sheets.

The first issue is that of establishing the scientific basis for assessing the extent of natural variations and the impact of human activities on global climate. This includes documenting major variations in the earth climate (general circulation of the atmosphere and global water cycle, ocean transport and heat storage, global ice mass balance), monitoring natural and anthropogenic forcing factors, and quantifying the response of the climate system to forcings, in particular the feedback mechanisms associated with cloud and land surface processes.

The second issue is that of determining the extent to which projected changes in global climate will affect local or regional weather and weather-related phenomena, such as rain or snow. This involves both applied weather forecasting research and fundamental investigation of the influence of large-scale changes in mean atmospheric circulation and surface boundary conditions on weather statistics (Rind 1999).

The third issue, largely raised by paleoclimatic and historical evidence of relatively abrupt past climatic variations, leads to investigating the dynamics of the coupled atmosphere–ocean–land–ice system, the global ocean circulation, the ice sheet mass balance, etc. that underpins climate variability, and experimenting with model predictions of climate variations on seasonal-to-interannual and longer timescales. Exploring climate variability can be based on analyzing both observed or reconstructed records of past global changes (historical or paleoclimatic), and ensembles of climate predictions generated by free-running numerical models of the interactive atmosphere, ocean, ice, and land surface system.

Table 1. Overarching NASA earth system research questions organized in a progression from documenting key global variations and understanding the operative processes, to predicting changes that may occur in the future. Italicized questions concern the physical aspects of global change.

NASA Earth Science Research Questions

How is the global earth system changing?

- *How are global precipitation, evaporation, and the cycling of water changing?*
- *How is the global ocean circulation varying on interannual, decadal, and longer timescales?*
- How are global ecosystems changing?
- How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and that of new substitutes increases?
- *What changes are occurring in the mass of the earth's ice cover?*
- What are the motions of the earth and the earth's interior, and what information can be inferred about earth's internal processes?

What are the primary forcings of the earth system?

- *What trends in atmospheric constituents and solar radiation are driving global climate?*
- What changes are occurring in global land cover and land use, and what are their causes?
- How is the earth's surface being transformed, and how can such information be used to predict future changes?

How does the earth system respond to natural and human-induced changes?

- *What are the effects of clouds and surface hydrologic processes on the earth's climate?*
- How do ecosystems respond to and affect global environmental change and the carbon cycle?
- *How can climate variations induce changes in the global ocean circulation?*
- How do stratospheric trace constituents respond to change in climate and atmospheric composition?
- *How is global sea level affected by climate change?*
- What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

What are the consequences of change in the earth system for human civilization?

- *How are variations in weather, precipitation, and water resources related to global climate change?*
- What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
- What are the consequences of climate and sea level changes, and increased human activities on coastal regions?

How well can we predict the changes to the earth system that will take place in the future?

- *How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?*
- *How well can transient climate variations be understood and predicted?*
- *How well can long-term climatic trends be assessed or predicted?*
- How well can future atmospheric chemical impacts on ozone and climate be predicted?
- How well can cycling of carbon through the earth system be modeled, and how reliable are future atmospheric concentrations of carbon dioxide and methane predicted by these models?

Turning to paleoclimatic information is an attractive option, which is being actively pursued by other USGCRP partners, particularly the National Science Foundation. The analysis of paleoclimatic data is a powerful discovery tool for exploring the range of past climate changes, but proxy climate indicators are usually insufficient to constrain the climate system and provide quantitative answers about operative mechanisms. On the other hand, it is simply not acceptable to wait for many decades into the future until decadal or centennial variations will be fully documented by modern observations.

For this reason, essential elements of climate research are the development of comprehensive climate system models (or equivalent hierarchy of interactive component models), a verification strategy to build up confidence in the accuracy of these models, and the capability to assess the consequences of global changes that can affect humans and the environment. Although not widely recognized, verification against observed climate statistics has its own limits for the purpose of testing models and reducing the uncertainties in climate simulations. The fundamental reason is that the observed record of the earth's climate is one single realization of the chaotic dynamics of the earth system. We know, from numerical experimentation with ensembles of independent model runs under the same boundary conditions, that free-running climate predictions diverge from each other in the course of long-term integrations. There is no reason why the observed record should coincide with any of these predictions, even if they were produced by a perfect model. Expected differences are on the same order of magnitude as the variance of independent model runs. This irreducible margin of uncertainty is usually too large to use observed mean climate quantities for unambiguously identifying and correcting weaknesses in model formulation of individual component processes (Cane et al. 1995).

Thus, the model verification strategy must reach down to the level of component processes, which operate on relatively short "internal" timescales and can effectively be treated as predictable consequences of the more slowly varying large-scale state. Process representations may then be tested against duration-limited but detailed observations of both processes and governing large-scale parameters, in the framework of short model runs that have not yet substantially diverged from the observed state of the climate system.

The recognition of the need to verify not just model predictions of mean climate variables, but also the internal working of models at the process level, is the scientific underpinning of NASA's programmatic vision: a three-tier program consisting of 1) systematic global measurements of a limited set of key climate variables; 2) investigations of component processes that may call for one or more "exploratory" global observations from space, dedicated field and airborne measurement campaigns, and laboratory and theoretical studies; and 3) the development of a hierarchy of climate models to integrate results from process studies and fill the gaps between incomplete systematic observations.

Systematic measurements acquired by research and operational observing systems are indispensable to detect the occurrence of significant variations in the major components of the climate system and independently determine changes in representative variables that currently cannot be inferred from other measured quantities (e.g., the structure of precipitating clouds and associated precipitation that cannot yet be reliably related to bulk atmospheric variables). Systematic measurements need to be maintained consistently for a long period of time, but need not embrace all environmental variables. Indeed, it is NASA's goal to continue working with the scientific community and identify a limited set of high-priority climate parameters that should be monitored from space. In the long term, the expectation is that the needed systematic measurements can be obtained from, or implemented in partnership with, operational agencies and maintained with appropriate continuity and calibration consistency. NASA recognizes the crucial need for climate-quality datasets and will continue to support the scientific analysis of systematic measurements from both research and operational observing systems, as well as remote sensing algorithm science, calibration, and validation.

Exploratory measurements, data analysis, and modeling are needed to enable detailed investigations of the operative physical, chemical, and/or biological processes. Exploratory global measurements and dedicated field campaigns will be required to resolve the spatial and temporal scales that characterize internal process dynamics and to sample the expected range of variations in governing large-scale atmospheric, oceanic, ice, or land parameters (but not necessarily observe the interannual, decadal, or centennial variability of all such parameters). Altogether, the NASA earth science strategy is following a new approach to program implementation, focused on answering specific scientific questions (identified in Table 1) through investments in observational research and modeling.

3. Climate variability and trends

For the purpose of identifying significant changes in the state of the physical climate system, three major components need to be considered, each involving distinctly different timescales: the atmospheric circulation (hours to weeks), the oceanic circulation (weeks to centuries), and the polar ice sheets (years to millennia).

a. The global water cycle

According to model predictions, the most significant manifestation of climate change for humans and the environment is an intensification of the global water cycle, leading to increased global precipitation, faster evaporation, and a general exacerbation of extreme hydrologic regimes, floods, and droughts. A more active water cycle would also be expected to generate more frequent and/or more severe weather disturbances. We know there have been generally upward trends in measured surface temperatures, amounting to a significant global mean temperature increase over the last 20 years. We also know that, during the same period, upper-air (tropospheric) temperatures have experienced contrasted, positive or negative changes in different regions of the earth, which add up to no clear global-mean trend (Bengtsson et al. 1999; NRC 2000). Average precipitation over the United States appears to have increased by 5%–10% during the last century, much of the change resulting from an increase in the frequency and intensity of heavy rainfall. On the other hand, global records of cloud cover (Rossow and Schiffer 1999), precipitation (Arkin and Xie 1994; McCollum and Krajewski 1998; Lin and Rossow 1997), and water vapor (Randel et al. 1996) are not yet accurate nor extensive enough to unambiguously identify significant global trends. As its highest priorities for systematic observation, NASA selected three key existing or potential space-based measurements that can serve, in conjunction with ongoing operational observations, to identify major changes in atmospheric circulation and the global water cycle: global atmospheric temperature and humidity, global precipitation, and continental soil moisture. In addition NASA supports a major research effort to understand and predict the role of clouds in regulating radiation transfer in the atmosphere and radiation fluxes at the earth's surface.

Atmospheric temperature implicitly determines the large-scale flow of the atmosphere, including dynamical instabilities that cause cyclogenesis. Atmospheric water vapor is the principal source of energy that feeds the development of weather systems, and also a strong absorber of infrared radiation with a large impact on the planetary greenhouse effect. The NASA Earth Observing System (EOS) program made a major scientific and technological investment in the development of the experimental Atmospheric Infra-Red Sounder (AIRS) instrument (Aumann and Pagano 1994). The combination of AIRS, the Advanced Microwave Sounding Unit (AMSU), and the Humidity Sounder for Brazil (HSB) deployed on the EOS *Aqua* mission (2001–2006) is expected to greatly enhance the accuracy of global atmospheric temperature and humidity soundings and, for the first time, approach globally the utility of conventional balloon soundings available over continents. Following upon this investment, NASA's long-term strategy is to enable similar research-quality measurements on operational environmental satellites. To this effect, NASA cooperates with the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) in the realization of a joint NPOESS Preparatory Project (NPP), also known as the "Bridge Mission," which will test the prototypes of next-generation operational atmospheric sounders (including a new Advanced Technology Microwave Sounder developed by NASA) and assure the continuity of climate-quality atmospheric temperature and humidity measurements beyond the EOS *Aqua* mission through the period 2006–2012.

Global precipitation is the principal indicator of the rate of the global water cycle. Changes in precipitation over continents have immediate implications for agriculture and natural ecosystems, river flow, and the replenishment of freshwater resources. At high latitudes, solid precipitation drives the mass balance of glaciers and polar ice sheets. Establishing the existence of significant global trends requires dense, global rainfall measurements that can only be acquired by a combination of surface and space-based measurements (Xie and Arkin 1997). The experimental *Tropical Rainfall Measuring Mission (TRMM),* realized jointly by NASA and the Japanese National Space Development Agency (Kummerow et al. 2000), demonstrated the capability of a nadir-looking radar to resolve the vertical structure of precipitating clouds and thereby allow considerably more accurate estimates of instantaneous precipitation rates (Fig. 1). *TRMM* results, validated by several field measurement

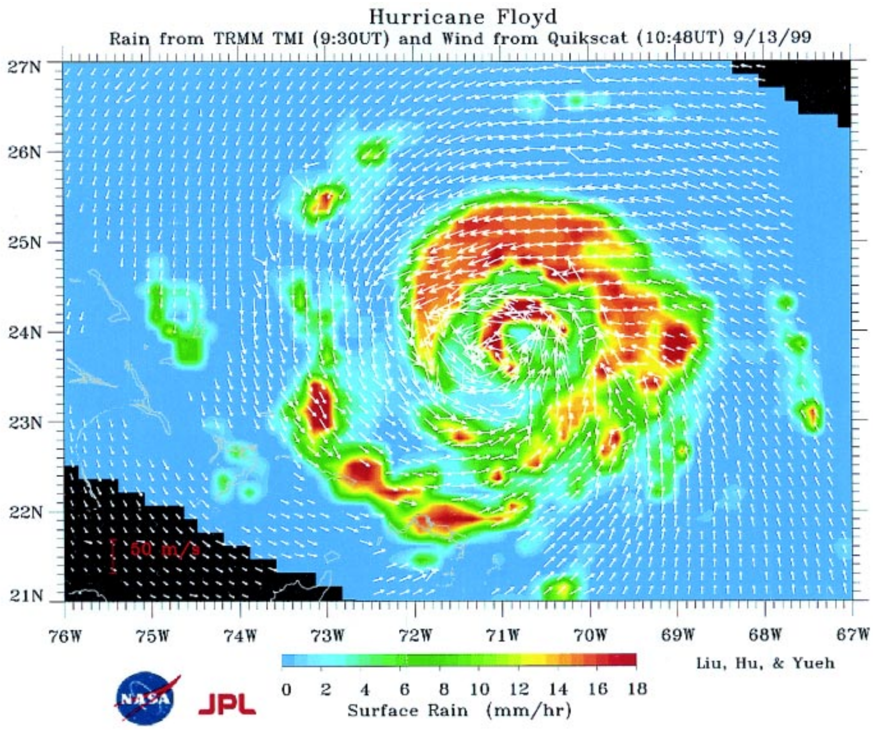

FIG. 1. Precipitation and winds observed over the Atlantic Ocean, as Hurricane Floyd is approaching Florida on 13 Sep 1999. Precipitation rate in deduced from the distribution of ice and water drops measured by active and passive microwave sensors on the Tropical Rain Measuring Mission spacecraft. Ocean surface winds are deduced from microwave backscatter measured by the Seawinds instrument on Quikscat.

campaigns (Kwajalein Experiment in the tropical Pacific, Convection and Atmospheric Moisture Experiments at various locations in the Tropics, the Large-Scale Biosphere–Atmosphere project in Brazil), showed that quantitative rainfall estimates may be inferred from passive microwave measurements only, provided retrieval algorithms are calibrated against nadir-looking radar data. This seminal finding enables conceiving a global precipitation measuring system based on observations by one active radar satellite and a constellation of six to eight passive microwave imaging spacecraft in staged polar orbits. A two-frequency radar on a high inclination orbit is needed to cover high latitudes and extend the range of retrievals to include solid precipitation. A constellation of passive sensors is needed for frequent sampling of precipitation events, at intervals of about 3 hours. NASA's strategy is to enlist the participation of several domestic and international partners in a full-scale demonstration with an experimental constellation that could eventually lead to an operational global rainfall measuring system in the future.

Closing the water budget over all regions of the world is a central objective of climate research. Changes in soil moisture have a major impact on terrestrial life and human uses. Soil moisture is also a controlling parameter of evaporation from the land surface (mainly plant-mediated evapotranspiration) and a predictive factor for summer rainfall over continents (Koster et al. 2000). Remote sensing of soil moisture in terrain covered by substantial vegetation poses considerable scientific and technical challenges. Extensive experience with airborne sensors [notably the Electronically Scanned Thinned Array Radiometer (ESTAR) microwave radiometer] showed that the signature of soil moisture under a low-density vegetation canopy is best observed at relatively low microwave frequencies on the order of 1.4–3 GHz (Fig. 2). At such frequencies, meaningful ground resolution can be achieved from space only with a very large antenna. This is a significant challenge that has hampered space-based soil moisture measurement so far. The European Space Agency is considering an experimental Soil Moisture and Ocean Salinity satellite project with relatively modest ground resolution on the order of 50 km. NASA, for its part, continues to study several experimental remote sensing concepts, using active (radar) and/or passive (radiometer) microwave techniques, that may be used in a future exploratory mission to observe soil moisture and freezing/thawing transition at spatial resolution on the order of 1–10 km (Running et al. 1999).

Clouds are essential elements of the climate system because of their controlling impact on the earth's radiation balance, atmospheric radiative heating or cooling, and surface radiation. Net surface radiation is a major component of oceanic and continental energy budgets, and an important boundary forcing that drives the ocean circulation and land surface processes. Since atmospheric general circulation models are not yet advanced enough to enable accurate computations of radiant energy fluxes at particular locations and times, it is essential to maintain the capability to infer surface radiation fluxes directly from observations of the relevant atmospheric variables (temperature and humidity profiles) and cloud parameters. The primary sources of information for this purpose are temperature and humidity profile data (see above) and visible/infrared imaging radiometer data. The latter is being provided by the Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument on EOS *Terra* and *Aqua* (1999–2006) and an international array of geostationary meteorological satellites. In the long term, NASA will rely on NPOESS for the acquisition of moderate-resolution radiance data that can be utilized to characterize the earth's cloud cover. To this effect, NASA participates in the development of the Visible and Infrared Imaging Radiometer Suite (VIIRS), led by the NPOESS program, and the realization of the joint NPP mission that will carry the VIIRS prototype and provide continuity for climate-quality moderate-resolution radiance measurements through the period 2006–2012.

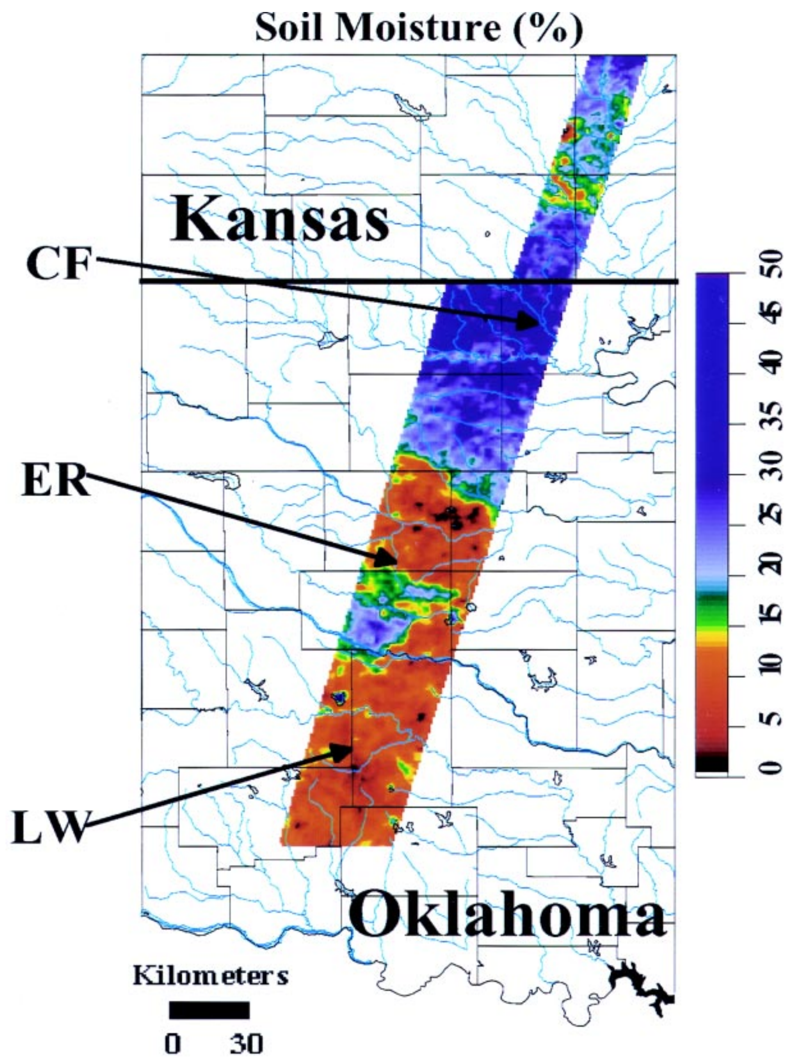

FIG. 2. Soil moisture map deduced from the ground microwave emission, measured by the airborne ESTAR microwave radiometer over KS and OK during the Southern Great Plains Hydrology Experiment in summer 1997.

b. The global ocean circulation

The oceans redistribute about half the excess radiant energy received by the planet in the Tropics, and are the source of about 85% of water present in the atmosphere. We know that the oceans can store substantial amounts of heat over seasonal or longer periods (Levitus et al. 2000), thus reducing transient variations in the earth climate. We know that changes in ocean circulation, and resulting changes in sea surface temperature, govern climatic variations such as ENSO and, probably, the North Atlantic/Arctic oscillation. The oceanic circulation also controls the supply of nutrients that feeds marine productivity and modulates biogeochemical processes, notably the global carbon cycle. In principle, initializing predictions of the World Ocean circulation requires global observations of the whole range of energy-containing ocean eddies, including a large contribution from scales of motion as small as 10–100 km. This is a very demanding observational requirement. A research strategy aiming to meet this requirement must rely on a combination of observation and modeling including the following:

- High-precision in situ oceanographic measurements, primarily by various automatic observing systems including surface moorings (e.g., Tropical Atmosphere–Ocean buoy array), subsurface drifting and profiling floats (e.g., Array for Real-Time Geostrophic Oceanography), and automatic measuring equipment on commercial vessels, to acquire essential surface and subsurface data.
- Space-based observations to resolve all significant scales of motions in the ocean circulation. Remote sensing of changes in the interior of the ocean relies on the detection of small "signatures" that appear at the ocean surface or in space. Among these signatures are changes in surface roughness (internal gravity waves and wind stress), surface topography (heat content and horizontal pressure gradi-

ents associated with currents), and time-dependent earth gravity field (ocean water mass distribution). In 1997, for instance, observed changes in tropical Pacific ocean topography indicated an impending El Niño event, long before any significant change in sea surface temperature could be detected, and likewise the subsequent La Niña phase (Fig. 3).

- Computer models of the ocean general circulation that simulate all key ocean processes. Such models will assimilate in situ and remotely sensed data and produce complete descriptions of the state of the ocean circulation.

NASA's principal contributions to physical oceanography are measurements of ocean surface topography and winds. The *TOPEX/Poseidon* mission, realized in cooperation with France and active since 1992, has demonstrated the capability to measure the mean sea surface height with single-pass accuracy of 4 cm (2 cm after spatial and temporal averaging), that is, an order of magnitude improvement over previous *Seasat* and *Geosat* observations (Fu et al. 1994). Such very high precision is needed for quantitative investigations of the ocean circulation and heat transport, tidal motions and energy dissipation, changes in subsurface heat content, and global-mean sea level rise (Wunsch and Stammer 1998). *TOPEX/Poseidon* provided the first testbed for detailed evaluation of global ocean circulation models (Fu and Smith 1996). Global sea level data derived from the mission also provided the first evidence that the entire ocean gained heat during the 1997–98 El Niño (Nerem et al. 1999). The *Jason* mission, also realized in cooperation with the French space agency, will continue high-precision ocean surface height measurements, beginning in early 2001. *Jason* will be the principal source of high-density ocean altimetry data for the Global Ocean Data Assimilation Experiment, an international initiative for global ocean circulation modeling and prediction.

Current coverage with only one nadir-looking precision altimeter on an inclined orbit is the result of a trade-off between spatial and temporal sampling and misses most small-scale eddies. Two or more nadir-looking missions, or a "wide swath" interferometric radar altimeter system (Rodriguez et al. 2000), are being proposed to sample the full spectrum of ocean eddy kinetic energy. Further NASA efforts to continue and/or enhance ocean topography measurements from space will be pursued in cooperation with environmental agencies in the United States and abroad, the long-term objective being to transfer this mature observing capability to U.S. and European operational satellite programs.

Precise knowledge of the earth's gravity field and center of mass is needed to translate

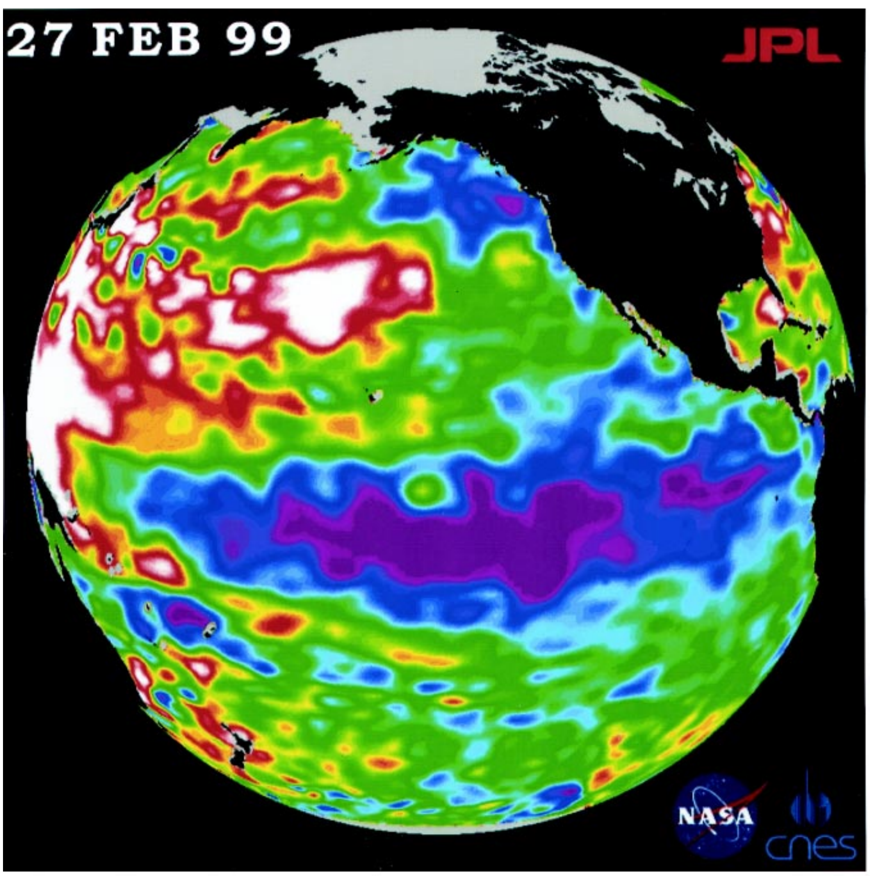

FIG. 3. Sea surface height anomaly relative to normal conditions, observed by the U.S.–French satellite TOPEX/Poseidon, during the strong La Niña phase that followed the 1997/98 El Niño. Ocean height is depressed in the central tropical Pacific, corresponding to cooler temperatures above the thermocline (blue and purple colors represent ocean surface heights 5–13 cm and 14–18 cm below normal, respectively). Yellow, red, and white indicate regions where the ocean surface is higher than normal, up to 24 cm.

raw satellite altimetry data into useful dynamical information, that is, the height above the reference surface of the earth's gravitational potential (geoid). The cooperative German–U.S. Challenging Minisatellite Payload mission, launched in July 2000, is the latest in a series of satellite missions that contributed to the systematic refinement of earth gravity field models through precise orbit tracking (ground-based satellite lidar ranging and space-based differential Global Positioning System measurements). The exploratory *Gravity Recovery and Climate Experiment (GRACE)* mission, to be launched by NASA in 2001, is expected to yield yet another major improvement in knowledge of the earth gravity field and determine the geoid to an unprecedented accuracy of 1–2 cm at spatial scales larger than 200 km. It is anticipated that space-based gravity measurements may eventually become sensitive enough to detect the gravitational signature of changes in the distribution of seawater mass (in effect ocean bottom pressure) and determine vertically integrated ocean currents. NASA is investing in the further development of space-based earth gravity measuring techniques that may open a new avenue of "photonless" earth remote sensing (NRC 1997).

Accurate surface wind information is essential to drive global or regional ocean circulation models (Millif et al. 1999). On account of the small width of ocean currents, wind observations are required at a horizontal resolution of 10–20 km for adequate estimation of wind stress curl that determines vertical motions. The NASA active microwave scatterometer (NSCAT) deployed on the Japanese space agency's *Advanced Earth Observing Satellite-1* (*ADEOS-1*) mission demonstrated the effectiveness of this technique for accurate measurement of ocean vector wind, albeit at relatively coarse resolution (Freilich and Dunbar 1999). The next-generation Seawinds scanning microwave scatterometer, developed by NASA under the EOS program, has already been launched on the *Quikscat* rapid-deployment mission. The follow-on *ADEOS-2* mission (to be launched by Japan in 2001) will carry the second flight model of the same instrument. Seawinds microwave backscatter measurements also provide unique observations of sea-ice cover and drift velocity, which complement sea-ice measurements made operationally by the Special Sensor Microwave/Imager imaging microwave radiometer on Defense Meteorological Satellite Program satellites and yield significantly higher spatial resolution, on the order of 10 km (Liu et al. 1999). The extent and concentration of sea ice is a sensitive indicator of climate change, as the annual cycling of the ice cover is determined by a finely tuned balance between heat exchanges with the ocean and atmosphere, and the absorption of solar radiation during summer (Vinnikov et al. 1999).

Ocean wind data are also a very significant input for operational weather and sea state forecasting applications. For this reason, global ocean wind observations will be continued for the foreseeable future by the NPOESS program, currently planning to use a passive polarimetry technique developed by the U.S. Navy. Pending flight testing of this technique on the navy's *Coriolis* experimental mission in 2002, NASA maintains the option of flying advanced active vector wind sensors on Japan's Global Change Observation Mission series or other suitable platforms in the future.

Sea surface temperature (SST) is the principal governing parameter of energy exchanges between atmosphere and oceans, and a primary indicator of global climate change. SST is measured routinely by existing ocean monitoring systems, including operational environmental satellites, drifting or moored meteorological buoys, and voluntary observing ships. Improvements in accuracy and/or all-weather availability of space-based SST measurements are expected from the EOS *Terra* and *Aqua* missions. If confirmed, these advances will be implemented on NPP and operational NPOESS missions in the future.

c. *Mass balance of polar ice sheets*

We know that ice sheets alternatively advanced and retreated over past glacial cycles, causing considerable variations in the global-mean sea level, in excess of 100 m. We also know that any net change currently occurring in the mass of the Greenland and Antarctic ice sheet must be quite small, consistent with a rate of sea level rise of a few millimeters per decade. Little is known, quantitatively, about the potential for rapid changes in polar ice sheets, given the range of expected variations in polar climates (Bamber et al. 2000). Repeated airborne surveys supported by NASA (Krabill et al. 2000; Thomas et al. 2000) have recently provided the first insight in the current mass balance of the Greenland ice sheet (Fig. 4). NASA is now ready to initiate systematic topographic surveys of both polar ice caps with the *Ice, Land, and Cloud Elevation Satellite (ICEsat)* to be launched in 2001, using high-precision lidar ranging from space. A repeat mission is tentatively planned later in the decade. Imaging radar data are also important to survey the ice sheets (Joughin et al. 1999) and reveal active regions where the sheet's internal dynamics are at work (see section 5d).

4. Climate forcings

Solar radiation is the only known cause of climate change that is truly exterior to the earth system, although other factors (e.g., solar or cosmic rays) may also have some influence. Human activities also cause changes in the natural environment that may significantly modify global climate. Both types of influences are considered as *forcing factors* external to the earth climate system.

a. Solar radiation

We know that the sun's radiant energy output varies in relation with the quasiperiodic cycling of solar activity. Currently, cyclic variations in total solar irradiance (TSI) incident upon the earth are believed to be too small (on the order of 0.1%) to directly cause more than barely detectable changes in tropospheric climate. However, TSI changes may have been significantly larger over the last several centuries. Furthermore, solar variability is much larger (in relative terms) at short wavelengths and induces considerable changes in the chemical composition, temperature, and circulation of the stratosphere, as well as in the higher reaches of the upper atmosphere. The extent to which solar-induced stratospheric changes can affect the troposphere is a matter of current scientific study (Haigh 1996; Shindell et al. 1999). Under any circumstances, accurate TSI and spectrally resolved irradiance data are needed to assess the fraction of observed climate variability that can be attributed to changes in solar activity. NASA has taken the lead in solar radiation measurement and has already acquired a 20-yr record (Fig. 5) based on overlapping measurements by the Earth Radiation Budget (ERB), and Active Cavity Radiometer Irradiance Monitor (ACRIM) radiometers on successive *Nimbus, Solar Maximum, Upper Atmosphere Research Satellite* (*UARS*), and *Earth Radiation Budget Experiment* missions (Willson 1997; Dessler et al. 1998).

A rigorous calibration procedure is essential to achieve the needed long-term consistency in TSI measurements. The NASA strategy for continued TSI observation is founded on the planned overlap of successive satellite missions, onboard monitoring of instrument aging, and periodic intercomparison with a laboratory-calibrated reference sensor on the space shuttle (as insurance against the contingency of a hiatus in the satellite record). In the near future, two overlapping missions will measure solar radiation: the *ACRIMSAT* mission launched in 1999, carrying the Active Cavity Radiometer Irradiance Monitor radiometer, and the *Solar Radiation and Climate Experiment* mission to be launched in 2002. The latter will carry the star-calibrated far-ultraviolet Solar Stellar Irradiance Comparison Experiment spectrometer, developed under the EOS program, as well as the prototype of a new solar radiometer suite, which will be flown systematically on NPOESS satellites in the future. The operational solar monitoring system on NPOESS will combine the full-spectrum Total Irradiance

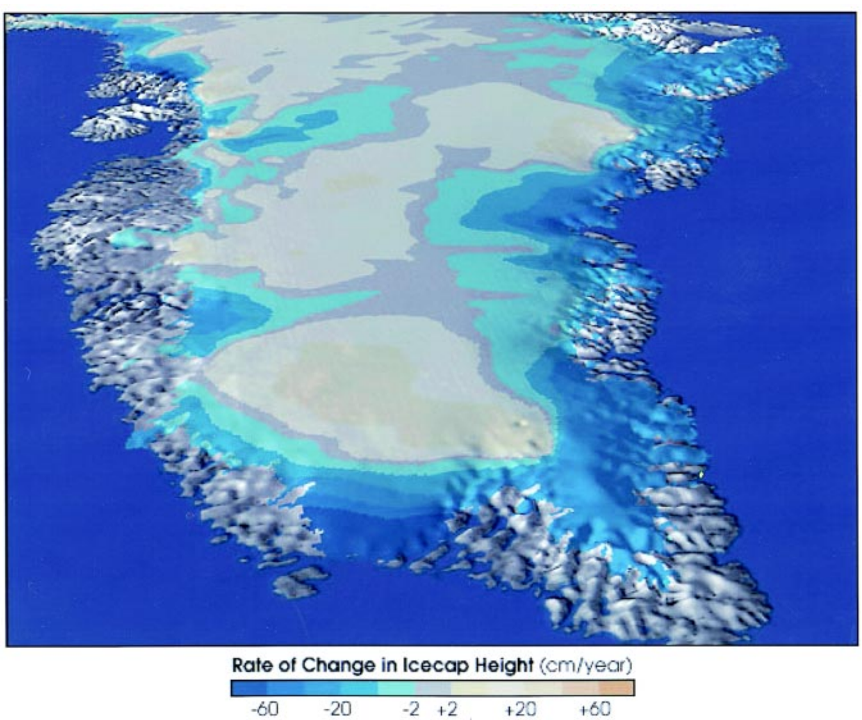

FIG. 4. A NASA study showed that the lower-altitude regions of the Greenland ice sheet are losing height (and ice mass) at rates reaching 1 m yr^{-1} at the periphery. On the other hand, ice is accumulating over high-altitude regions in the interior. Altogether, the mass budget of the Greenland ice sheet was almost balanced in recent times, with a net loss corresponding to a global mean sea level rise of 0.1 mm annually.

Monitor radiometer and the Spectral Irradiance Monitor spectrometer covering the range from ultraviolet radiation (200 nm) to shortwave infrared (2500 nm).

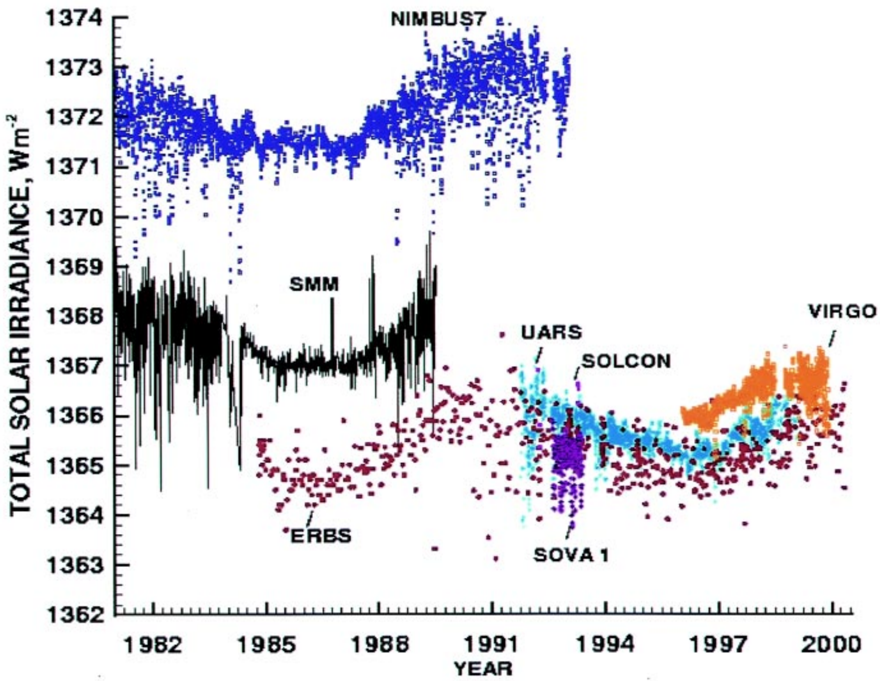

FIG. 5. In-space solar radiation measurements since *Nimbus-7* and the Solar Maximum Mission in 1981. A consolidated 20-yr record of total solar irradiance can be derived from these measurements by eliminating the biases between successive instruments.

b. Greenhouse gases and the global carbon cycle

Monitoring the concentrations of long-lived trace constituents that absorb infrared radiation, such as carbon dioxide, nitrous oxide, and methane, is best done from surface stations. NASA contributes to the multiagency monitoring effort, spearheaded by the National Oceanic and Atmospheric Administration (NOAA), with the Advanced Global Atmospheric Gases Experiment (AGAGE), a relatively sparse network for frequent and very precise measurement of several greenhouse and ozone-depleting gases. The AGAGE stations complement a larger international network that monitors greenhouse gases at much lower sampling frequency. Quantitative knowledge of global sources and sinks still eludes us, however, to the point that a significant "deficit" exists in current estimates of the earth's carbon budget. NASA observations provide a basic data resource for quantifying exchange processes, involving marine and terrestrial ecosystems, that govern the global carbon cycle. These global datasets are 1) ocean color measurements, which allow inferring the amount of chlorophyll in the upper ocean and estimating net primary productivity; and 2) multispectral radiometry data, which provide a basis for terrestrial ecosystems classification and estimation of above-ground biomass.

NASA currently relies on the acquisition of ocean color data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the *Orbview-2* satellite operated by Orbital Science Corporation (Fig. 6). Global ocean color observations will continue with the MODIS imaging radiometer on EOS *Terra* and *Aqua.* NASA also cooperates with several foreign space agencies to share multispectral image data and leads a multinational project (Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies) to compare ocean color observations from different satellite sensors with in situ optical and biological measurements in the ocean, and assemble a coherent time series of global biological productivity data spanning several decades.

Following upon the international global 1-km land cover data project based on operational Advanced Very High Resolution Radiometer observations, MODIS multispectral image data will become the primary source of information for estimating terrestrial productivity during the next five years. In the long term beyond the EOS *Terra* and *Aqua* missions, NASA will rely on the NPOESS program for systematic global mapping of the earth surface at moderate resolution. In consultations with NASA, NPOESS is developing the VIIRS multispectral imaging radiometer that will fulfill the principal observational needs for this application. The prototype instrument will be carried by the joint NPP mission, which will ensure forward continuity with the NPOESS program. Higher spatial resolution than global imaging data (on the order of 15–30 m) is required to derive accurate land cover inventories and estimate changes in carbon storage. For this purpose, NASA plans to continue systematic seasonal mapping of the global land surface using high-resolution image data from *Landsat-7* and successor missions, and/or data purchased from commercial earth observation satellite operators.

Chemically active, shorter-lived greenhouse gases experience complex variations that result from the interplay of multiple dynamical, physical, and chemical processes in the atmosphere. Variations in these reactive gases, particularly ozone, can induce significant changes in stratospheric temperature profiles and climate. Building on the long-term record provided by the Total Ozone Mapping Spectrometer (TOMS), the Stratospheric Aerosol and Gas Experiment (SAGE) and several instruments aboard (*UARS*), NASA plans to acquire the most accurate ever global climatology of stratospheric and upper-tropospheric ozone with a suite of new instruments that will be deployed on the forthcoming EOS *Aura* mission (especially the Tropospheric Emission Spectrometer). Continued systema tic measurements of ozone are planned, notably with the operational Ozone Mapping and Profiling Suite sensors on NPOESS.

c. Aerosols

We know that stratospheric aerosols, such as produced by large volcanic eruptions, most recently the eruption of Mount Pinatubo (McCormick et al. 1995), can cause significant warming of the stratosphere and cooling of the earth's troposphere and surface. Tropospheric aerosols, on the other hand, can produce either cooling or warming depending upon aerosol optical properties and the albedo of the underlying surface. Tropospheric aerosols can also influence climate indirectly by modifying the microphysical properties and life cycle of clouds (Ackerman et al. 2000; Taylor and Ackerman 1999), as well as precipitation (Rosenberg 2000). The specific effects of aerosols on atmospheric radiation strongly depend upon the variable distribution, sizes, shapes, and chemical compo sition of aerosol particles; understanding the complex processes that govern these aerosol parameters is a major scientific challenge.

Currently, no single observing technique or combination of techniques can document all relevant properties of aerosols globally. The problem is particularly challenging in the troposphere, where aerosol lifetime is only a few days and their distribution and composition are highly variable. Determining total aerosol

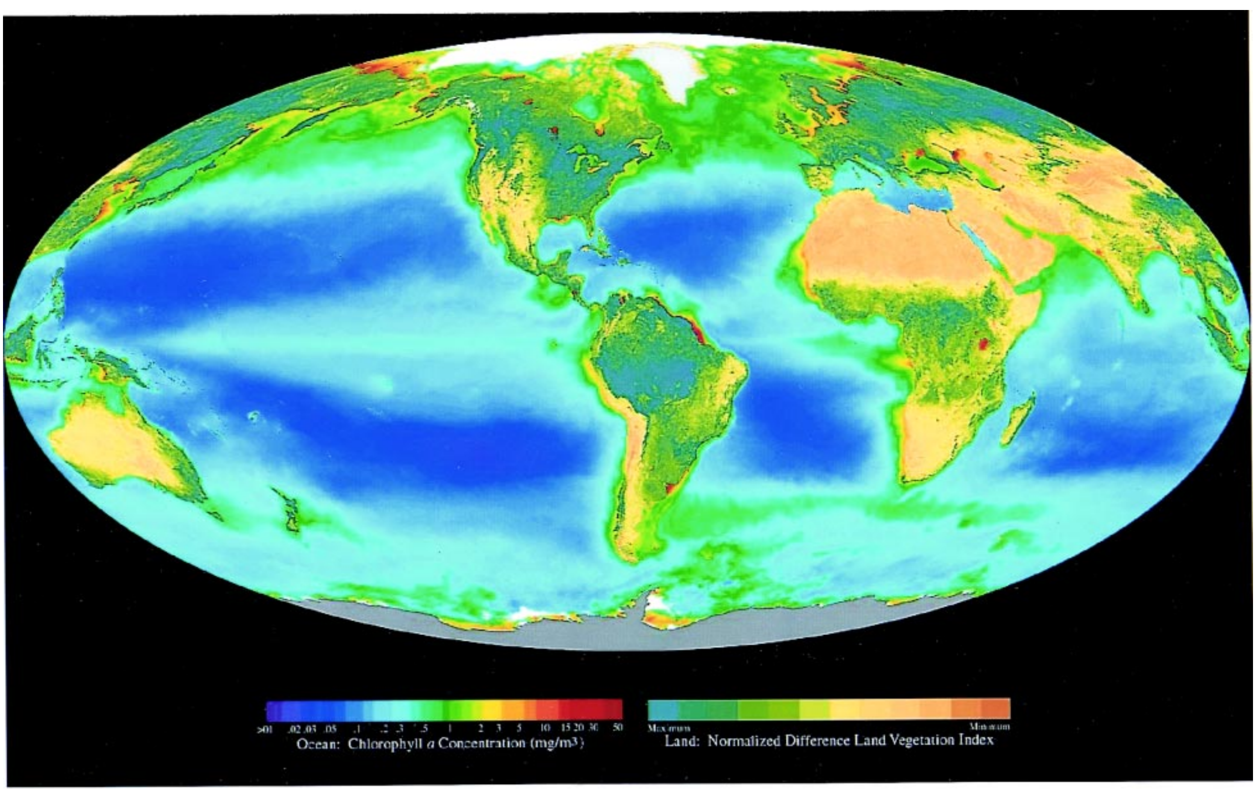

FIG. 6. Third anniversary image produced by the SeaWiFS project, depicting the global biosphere, the ocean's average chlorophyll concentration over the period Sep 1997 to Aug 2000, and a map of the normalized difference vegetation index over land during Jul 2000. In the oceans, yellow and green colors show regions where dense phytoplankton life exists, while abundant land vegetation is indicated by dark greens.

amounts, as well as spatial and temporal variations reflecting aerosol microphysical and chemical processes, is an important element of NASA's climate research program. The objective is ultimately to develop reliable aerosol chemistry and transport models that can be used to predict the climatic impacts of aerosols from all sources (King et al. 1999). Systematic NASA measurements include the following:

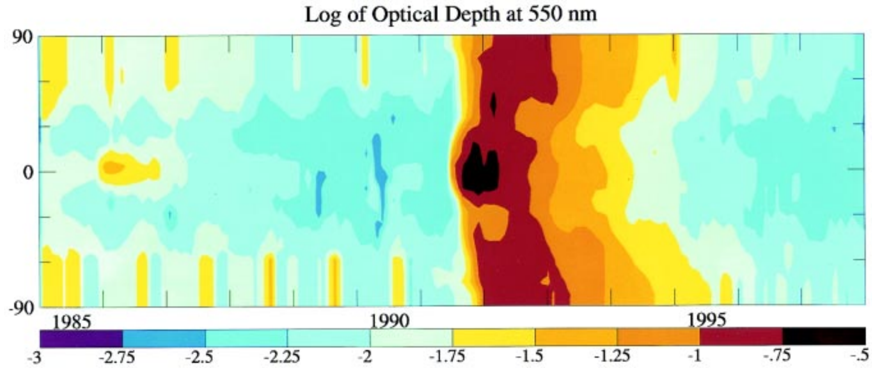

FIG. 7. Time–latitude record of aerosol optical depth in the stratosphere, measured by SAGE during the period 1985–97. In 1991, the Mount Pinatubo eruption injected a large amount of particulate matter into the stratosphere. The anomaly persisted for almost two years.

- global mapping of total-column aerosol content and mean particle size, based on the analysis of visible and near-infrared reflectance data from MODIS on EOS *Terra* and *Aqua,* SeaWiFS, and the Multi-angle Imaging Spectro-Radiometer sensor on *Terra;*
- global mapping of total-column aerosol content, based on the measurement of solar ultraviolet backscatter measurements by TOMS sensors on several Earth Probe missions and similar follow-on instruments (Ozone Monitoring Instrument on EOS *Aura,* Ozone Mapping and Profiling Suite on NPOESS); ultraviolet backscatter observations also allow discriminating between UV-absorbing aerosols (mineral dust, smoke) and nonabsorbing aerosols (sulfates, sea salt);
- stratospheric and upper-tropospheric aerosol profiles, inferred from solar occultation measurements by a series of SAGE missions (Fig. 7); and
- total aerosol measurements by the Aerosol Robotic Network of multispectral solar photometers installed by NASA at a number of sites (currently about 75) with the cooperation of local institutions around the globe.

In view of the complexity of aerosol microphysics, comprehensive airborne and field measurement campaigns, such as the Southern Africa Regional Science Initiative, are essential to validate and complement global measurements. In addition NASA has undertaken, in cooperation with the French space agency, a major experimental satellite mission (the *Pathfinder Instrument for Cloud and Aerosol Spaceborne Observations-Climatologie Etendue des Nuages et des Aerosols; PICASSO-CENA)* designed specifically to study the distribution and optical properties of aerosols. Following the Lidar In-space Technology Experiment on the space shuttle (Winker et al. 1995), *PICASSO-CENA* will be, in 2003, the first long-duration mission specially designed to probe the full depth of the atmospheric column with an active lidar sensor. Formation flying of *PICASSO-CENA* with the EOS *Aqua* spacecraft will allow simultaneous acquisition of lidar, MODIS, and Cloud and the Earth's Radiant Energy System (CERES) data. These measurements will enable determining separately aerosol particle density, optical properties, and optical depth, and inferring aerosol radiative forcing, essentially free from a priori model assumptions. In addition, observation of aerosol infrared absorption by the High-Resolution Dynamics Limb Sounder (HIRDLS) spectrometer on EOS *Aura* may yield new (experimental) diagnostics of aerosol types and distribution in the stratosphere.

5. Climate responses and feedback mechanisms

Among the multiplicity of mechanisms and processes that influence climate, NASA selected four high-priority research topics that are amenable to focused investigations involving intensive field measurements, exploratory global satellite surveys and data analysis, and specialized process-resolving model studies. These four research foci are 1) the controlling role of water vapor and clouds in radiation transfer and the earth's radiant energy balance, 2) land surface hydrologic processes and their effects on large-scale soil water storage and water resources, 3) the freshwater budget of the upper ocean and consequences for deep water formation and the global ocean circulation, and

4) "fast" dynamic phenomena in polar ice sheets and their potential impact on global-mean sea level.

a. Water vapor, clouds, and the planetary radiation balance

We know that water vapor is a strong absorber of infrared radiation and contributes more to the greenhouse effect of the atmosphere than all other greenhouse gases together. Atmospheric humidity responds strongly to changes in atmospheric temperature, thus constituting a net positive climate feedback mechanism. Our knowledge of atmospheric transport of water and transformations among its three physical states is far from sufficient to quantify water fluxes to the required accuracy, and fully understand the connections with the development of weather systems.

Liquid water and ice clouds are the principal factors controlling rapid fluctuations in radiant energy fluxes and radiative heating (or cooling) of the atmospheric column. The formation, life cycle, and optical properties of clouds remains the largest source of uncertainty in climate change predictions, due largely to the complexity of cloud microphysical processes and their linkage to the dynamics of weather systems. NASA has invested considerable efforts in the study of cloud processes and their impact on atmospheric radiation, locally and globally. Observations by the *Earth Radiation Budget Experiment,* the current EOS CERES project, and the international surface radiation network provide the basic information for relating time-averaged radiation fluxes to cloud distribution and optical properties (Wielicki et al. 1995). In parallel, the International Satellite Cloud Climatology Project provides basic 3-hourly global data for relating clouds to weather phenomena (Rossow and Schiffer 1999). As a result, considerable advances have been made in representing cloud and radiation processes in both general circulation and climate models. Observation requirements for further progress have kept pace with these advances; observational goals are now to 1) determine individually the principal cloud characteristics, such as water and ice content, particle size and optical properties, and cloud optical depth; 2) resolve the three-dimensional structure of cloud ensembles; and 3) relate cloud structure and properties to the weather systems and aerosol environment in which they are embedded.

In addition to systematic observation of the global cloud distribution by research and operational environmental satellites, NASA is planning a major exploratory satellite program to support fundamental cloud process studies. The program calls for the deployment of a constellation of three spacecraft flying in close formation on the same orbit:

- EOS Aqua satellite, carrying passive radiometric sensors that will measure radiation fluxes at the top of the atmosphere (CERES), cloud-top optical properties (MODIS), atmospheric temperature and humidity profiles (AIRS), and microwave absorption or backscatter by heavy ice particles and water droplets (Advanced Microwave Scanning Radiometer);
- *Cloudsat* exploratory satellite equipped with a millimeter-wave cloud profiling radar, which will probe the vertical structure of clouds of intermediate thickness, including nonprecipitating stratiform clouds and drizzle (Brown et al. 1995); and
- *PICASSO-CENA* exploratory satellite carrying a polarimetric lidar to observe particulate matter in the atmosphere at the lowest range of optical depths (aerosols and optically thin clouds).

The *PICASSO-CENA* and *Cloudsat* missions will be launched simultaneously in 2003 to match the orbit of EOS *Aqua* and will provide the first direct measurements of multilayered cloud systems. Two limb-viewing sensors on the EOS *Aura* mission (Microwave Limb Sounder, HIRDLS) will also observe temperature and water vapor profiles in the stratosphere and upper troposphere. Solar ultraviolet backscatter measurements by TOMS provide complementary information on cloud fraction and cloud-top altitude. Additionally, the Geostationary Imaging Fourier Transform Spectrometer technology demonstration mission, planned for launch in 2004, will provide high spatial and temporal tropospheric water vapor data to improve prediction of cloud generation and evolution. From these combined efforts, a major advance is expected in knowledge of the three-dimensional structure of clouds, and their relationship to weather systems globally.

NASA will continue to organize intensive airborne observation campaigns for characterizing microphysical processes and radiative transfer in the cloudy atmosphere, and cooperates with other agencies that provide needed surface-based observations, principally the Atmospheric Radiation Measurement program of the U.S. Department of Energy and the Surface Radiation Budget Network program of NOAA. The principal field campaigns planned in the near future will be part of the Cirrus Regional Study of Tropical Anvils and Layers, a research program to investigate high-altitude water vapor and ice clouds in storms and mesoscale weather systems. NASA also plans to support the development of a hierarchy of model tools, from microphysical models of cloud particle formation and growth, to cloud ensemble models that can be directly compared to single-column parametric formulations in climate models.

b. Land surface hydrologic processes

Freshwater is a critical resource upon which the existence of life depends. Long-range atmospheric transport and condensation of water vapor, precipitation, river runoff, and evapotranspiration from vegetated areas all contribute to determining the freshwater budget of land areas and the fate of water reserves available to ecosystems and human societies. These diverse phenomena have yet to be quantified with sufficient accuracy to enable hydrologic applications of climate predictions for flood forecasting and water system management. From a broader perspective, the functioning of the earth system can be envisioned as interconnected cycles of water, energy, carbon, and other nutrients. Hydrologic processes play a central role in connecting these cycles across land, atmosphere, and ocean. Soil moisture controls evaporation from land and plant transpiration. River flow carries nutrients and sediments to estuaries, providing an effective link between terrestrial and oceanic systems. Atmospheric transport connects the freshwater budgets of land, ice, and ocean reservoirs.

Within this wide research domain, NASA's priority in the next decade is to develop global measurements that contribute to fundamental understanding of land surface hydrologic processes. In addition to global precipitation measurements (see section 3a above), NASA is considering various space-based techniques to estimate soil moisture, the most extensive indicator of the state of the hydrologic system and an important initial value for prediction of summertime rainfall over large continental regions (Beljaars et al. 1996; Koster et al. 2000). The challenge is to detect the soil moisture signal from terrain covered by vegetation while, at the same time, achieving useful spatial resolution on the ground (on the order 10–30 km or better). Very large antennas are required to meet the latter requirement at the low microwave frequencies that penetrate a moderate vegetation canopy. NASA is studying a variety of passive and active microwave techniques that would enable observing soil moisture and changes in land surface conditions such as freezing and thawing. NASA also supports fundamental land surface process studies, including intensive in situ and aircraft observations, and participates in several continental-scale water and energy budget studies, notably the Global Energy and Water Cycle Experiment (GEWEX) Continent-scale International Project (Lawford 1999) and the GEWEX America Prediction Project over the continental United States as well as the Large-scale Biosphere–Atmosphere experiment over the Amazon River basin.

The interiors of the North American and Eurasian continents and high-altitude mountains receive much of their annual precipitation in the form of snow during winter months, with distinctive consequences for the seasonal regimes of the rivers they feed. The soil freeze/thaw transition determines the relative amounts of snowmelt and precipitation that contribute to runoff versus infiltration, and also triggers the onset of vegetation growth in spring. NASA expects that future exploratory satellite projects may allow observing these cold climate hydrologic phenomena on a global scale.

An exciting new prospect has been opened by the *TOPEX/Poseidon* mission, which demonstrated the capability to measure the stage height of large rivers and inland water bodies with a space-based radar altimeter (Fig. 8). The *ICESat* mission will demonstrate another means of acquiring similar data with much finer spatial resolution (170 m along track) using a lidar altimeter. Although river stage height can be conveniently observed in situ, the discharges of many of the world's rivers are not currently being monitored, or the data are not available to the scientific community. Homogeneous, readily accessible measurements of the stage of rivers and other inland water bodies would be a valuable source of global hydrologic information at a time when the world's water resources are being stressed and international disputes are arising about water sharing.

In a more visionary perspective, NASA is investigating the feasibility of gravity field measurements that may be sensitive enough to detect the minute gravitational signature of changes in the distribution of surface water over continents and the discharge/recharge of ground water. Such developments (to be tested for the first time by the exploratory *GRACE* mission in 2001) may usher revolutionary new photonless remote sensing methods that directly yield gravimetric measurements of changes in ground water storage or snow accumulation over continents, as

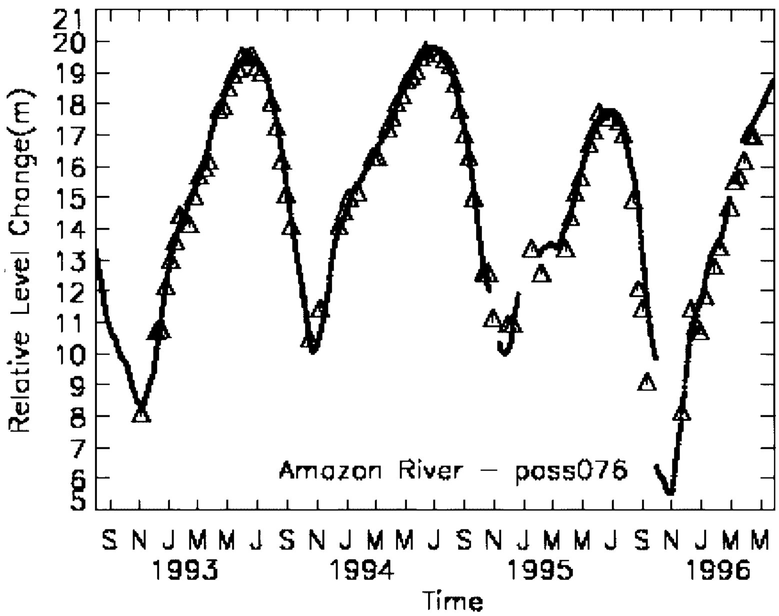

FIG. 8. Time series of stage heights measured over the same section of the Amazon River by the TOPEX/Poseidon altimetry satellite. Note the near-coincidence of TOPEX data (triangles) and in situ measurements at the Manacapuru River gauging station (solid line). The single-pass accuracy of TOPEX height measurements over a sufficiently wide water body is 4 cm.

well as similar changes in ocean mass distribution (NRC 1997).

c. *Impact of deep water formation on the global ocean circulation and climate*

The rate of formation of dense water that sinks to intermediate depths or to the bottom of the ocean has profound implications for the global ocean circulation, long-term oceanic storage of heat and chemicals, the cycling of nutrients, marine primary productivity, and carbon intake, in addition to direct impact on climate around ocean basins. There is theoretical and paleoclimatic evidence that the overturning circulation of the Atlantic Ocean is sensitive to a decrease in salinity of surface waters that may be caused by climate change (Broecker 1997). A transition from the current circulation regime of the Atlantic Ocean to another regime with significantly reduced rate of deep water formation would induce a major climatic shift in the North Atlantic region.

The sinking of surface water exposed to cold air is the primary mechanism that governs the thermohaline circulation of the ocean. Since air temperature at high latitude eventually falls below the freezing temperature of seawater, the ability of surfacial waters to sink into the deep ocean is controlled by preexisting salinity. Thus, the key to understanding the likelihood of a transition toward a markedly different oceanic circulation regime is accurate prediction of the freshwater budget of the World Ocean.

This is a tall order, considering the scarcity of oceanic precipitation, evaporation, or sea surface salinity data worldwide. Global measurements of sea surface salinity [to an accuracy of 1 practical salinity unit (PSU) or less, out of 35 PSU for standard ocean water] would constitute a breakthrough in the study of the oceanic fresh water budget. This appears achievable through careful analysis of multifrequency microwave radiometry data and joint retrieval of surface roughness, temperature, and salinity. Developing the relevant remote sensing techniques is a priority of the NASA physical oceanography program; encouraging preliminary results have been obtained with an experimental airborne low-frequency microwave radiometer.

d. *Ice sheet dynamics and sea level rise*

Could changes in the mass balance of the Greenland and Antarctic ice sheets accelerate to the point where substantial rise in global sea level would result over periods of a few decades, much faster than the current rate of 1–2 mm yr^{-1}? The traditional perception of continental ice sheets as a sluggish component of the earth system, evolving with literally "glacial" slowness, precludes rapid changes in melting rate or iceberg discharge. This reassuring view is being challenged by the realization that parts of the Antarctic ice sheet are undergoing considerable transformation. The first high-resolution radar survey of Antarctica (Radarsat Antarctic Mapping Mission) discovered massive ice streams, huge rivers of ice reaching far inland, and introduced a new paradigm for assessing the likelihood of relatively fast ice flows that could discharge vast volumes of ice in a matter of decades instead of centuries (Fig. 9).

NASA plans to continue exploring the dynamic regions of the Greenland and Antarctic ice sheets, and estimating the mass flow of major ice streams. For this purpose the tool of choice is a new synthetic aperture radar (SAR) "interferometry" method, based on combining the intensity and phase information from successive SAR images obtained at short time intervals, that allows rapid mapping of ice surface topography and velocity fields (Joughin et al. 1999). NASA is currently conducting a second Modified Antarctic Mapping Mission focused on observing the periphery of the ice sheet. NASA aims to pursue this line of investigation and acquire further SAR observations from future NASA-managed earth observation mission(s), commercial satellite operators, and/or international partners.

In addition, the NASA polar research program supports airborne surveys and field campaigns, aiming to acquire critical ice sheet measurements such as the depth of the ice column and the topography of the underlying terrain. Repeated airborne laser altimeter surveys of the Greenland icesheet in 1993–94 and 1998–99 provided the first clear indication of significant regional differences in polar ice mass balance and trends (Krabill et al. 2000; Thomas et al. 2000).

6. Consequences of climate change: The climate–weather connection

From a fundamental standpoint, one could argue that the ultimate goal of climate science is to relate the large-scale mean properties of the earth's atmosphere, ocean, ice, and biogeochemical environment to the basic laws of physics and chemistry operating at molecular scale. Linking phenomena across such a huge range of characteristic space and time scales cannot be done in one stroke. Realistic steps in that direction are bridging the gaps in observation and models between the planetary-scale circulation and the development of weather disturbances, and between synoptic weather systems and cloud ensemble dynamics, eventually reaching out to include microphysical processes.

Furthermore, climate is an abstract statistical concept: people are sensitive to weather phenomena, especially extreme events, or natural climate integrators like the length of the growing season, not climatic averages. We know that a disproportionately large fraction of the global energy and water fluxes that determine global climate is governed by the nonlinear dynamics of active weather systems. In particular, much of the rainfall in tropical and subtropical regions is associated with tropical cyclones, squall lines, and other mesoscale weather disturbances. Thus a crucial objective for climate science, from both practical and fundamental perspectives, is to determine the extent to which the frequency, intensity, and distribution of transient weather systems (and related precipitation, river flow, and freshwater recharge) are predictable, given the state of global climate, and the extent to which such statistics are liable to evolve with climate change (Easterling et al. 2000).

Connecting weather and climate processes is, in itself, a major challenge. Weather forecasters and practical water resource managers are striving for accurate deterministic predictions of time-dependent variations in atmospheric circulation, precipitation, or river flow but, at the same time, use empirical representations of flux-controlling processes that are rooted in current climate statistics and thus may be invalid under a different climate regime. Global change scientists, on the other hand, strive for fundamental understanding of the physical, chemical, and biological processes that govern climate, but do not normally make use of the enor-

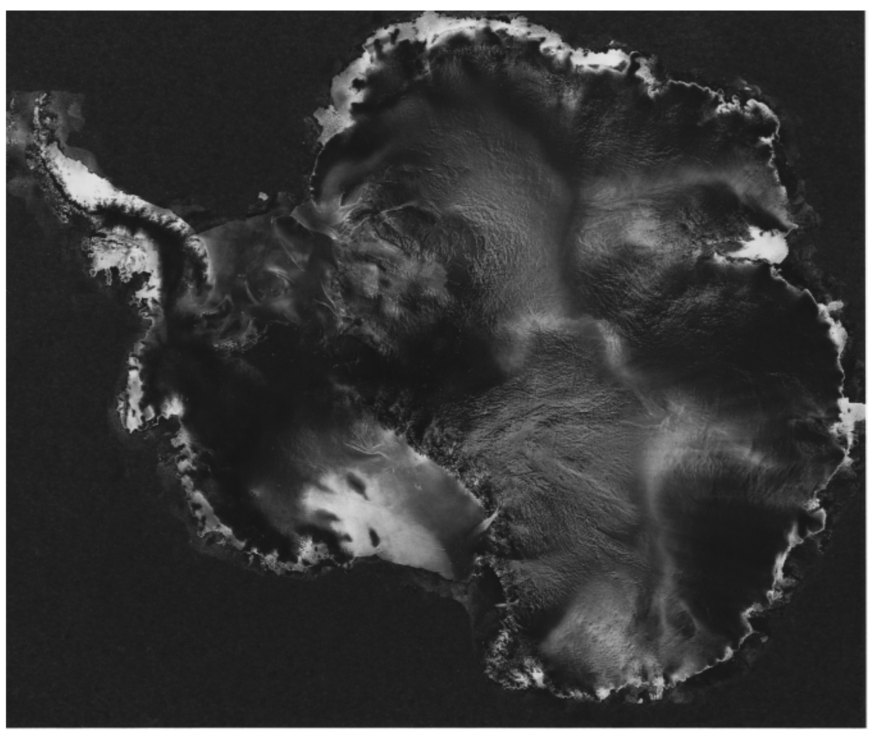

FIG. 9. SAR picture composite of the Antarctic ice sheet, produced by the Antarctic Mapping Mission, a joint project conducted by NASA and the Canadian Space Agency using Radarsat data. The full-resolution image shows ice streams reaching far inland.

mous flow of meteorological data that describes the evolution of weather systems globally. As a result, they are not well positioned to analyze the linkages between atmospheric–hydrologic processes and the atmospheric circulation transients in which they are embedded.

The NASA program aims to overcome this challenge and offers a unique combination of capabilities to study the climate–weather connection. NASA's EOS and successor programs will produce, for an extended period of time, research-quality data covering most aspects of the global physical environment. In particular, dense ocean wind observations acquired by the NSCAT sensor on Japan's *ADEOS-1* mission and the Seawinds sensor on NASA's *Quikscat* mission have been used effectively to characterize the path and life cycle of organized weather systems at sea, where the dynamics of weather disturbances are the simplest. NASA plans to pursue this successful technical avenue and deploy a second model of the Seawinds instrument on Japan's follow-on *ADEOS-2* mission, to be launched in 2001. Likewise space-based observation of precipitation rates in active storm systems, provided by *TRMM* and similar future missions, are instrumental in helping achieve quantitative precipitation forecasts, a foremost objective of the U.S. Weather Research Program. Also significant in this context is NASA's development of the experimental Geostationary Imaging Fourier Transform Spectrometer (GIFTS), which will demonstrate the application of advanced atmospheric sounding technologies in geostationary orbit. GIFTS would allow rapid tracking of moisture and dynamical features at high time and space resolution, initially over the United States and later over the Indian Ocean. GIFTS is being potentially viewed by NOAA as the next-generation operational geostationary atmospheric sounder, when successfully demonstrated.

NASA cooperates closely with NOAA in developing 1) precursor instruments for operational environmental satellite systems, 2) new data products originating from space-based observations, and 3) improved atmospheric circulation models and data assimilation schemes. The NASA Data Assimilation Office (DAO) at the Goddard Space Flight Center actually runs both its own research general circulation model (Fig. 10) and the operational model of the National Centers for Environmental Prediction, to develop and test new physical process formulations or data assimilation schemes. The DAO effort is particularly relevant for systematic exploitation of new observational data acquired by NASA satellites, notably global ocean surface wind measurements (NSCAT and Seawinds on *Quikscat* and *ADEOS-2*) and temperature/humidity profile measurements by advanced atmospheric sounders such as AIRS, AMSU, HSB on EOS *Aqua.* In this joint effort with NOAA, NASA's goal is to speed up the process by which new satellite data are incorporated into operational weather prediction, and thereby support the U.S. Weather Research Program.

7. Weather and climate prediction

One can argue that a scientific investigation is incomplete until it delivers predictions that can actually be compared with reality, and thus validated or invalidated by observation. In this matter, NASA is determined to follow the advice of the National Academy of Science (NRC 1998) to "apply the discipline of forecasting in atmospheric chemistry, climate, and space weather research in order to advance knowledge, capabilities for prediction, and service to society". The hallmark of NASA's modeling strategy is continued emphasis on the ability to test model products against observations of the earth system. For most atmospheric processes, this implies a capability to assimilate global measurements of rapidly evolving phenomena observed from space at high spatial and temporal resolution. NASA preferentially supports model developments geared to take advantage of this wealth of observational information. Modern data assimilation techniques, developed initially for numerical weather prediction, provide an effective mathematical framework for achieving this objective.

Experience has shown that the synergy between operational weather forecasting and the development of new observation systems or products is an effective engine of progress for both endeavors. Successive breakthroughs in global weather observation, atmospheric circulation models, and data assimilation methods have finally enabled extending the range of weather forecasts beyond one week, a goal set 30 years ago. A new generation of sensors is expected to provide global atmospheric data of unprecedented accuracy and resolution, which may enable a notable reduction in the number of forecast "busts" or major departures of model prediction from reality—possibly the most significant measure of weather prediction skill.

On longer timescales, the NASA Seasonal-to-Interannual Prediction Program, conducted by a numerical modeling team at the Goddard Space Flight Center and academic coinvestigators, aims to refine the formulation of coupled atmosphere–ocean–land models and the assimilation of new space-based observations of ocean surface topography, temperature, winds, and eventually continental soil moisture. Initial values of tropical ocean parameters are principally useful for ENSO prediction, while continent-scale soil moisture will significantly influence summertime precipitation forecasts over the interior of continents (Beljaars et al. 1996). Recent advances in seasonal prediction resulted from more realistic treatment of mesoscale weather systems, as could be expected since one of the most significant manifestations of transient ENSO anomalies is a shift in midlatitude storm tracks. NASA contributes to progress in all aspects of this research problem, from improvements of models and data assimilation methods to advances in global observation.

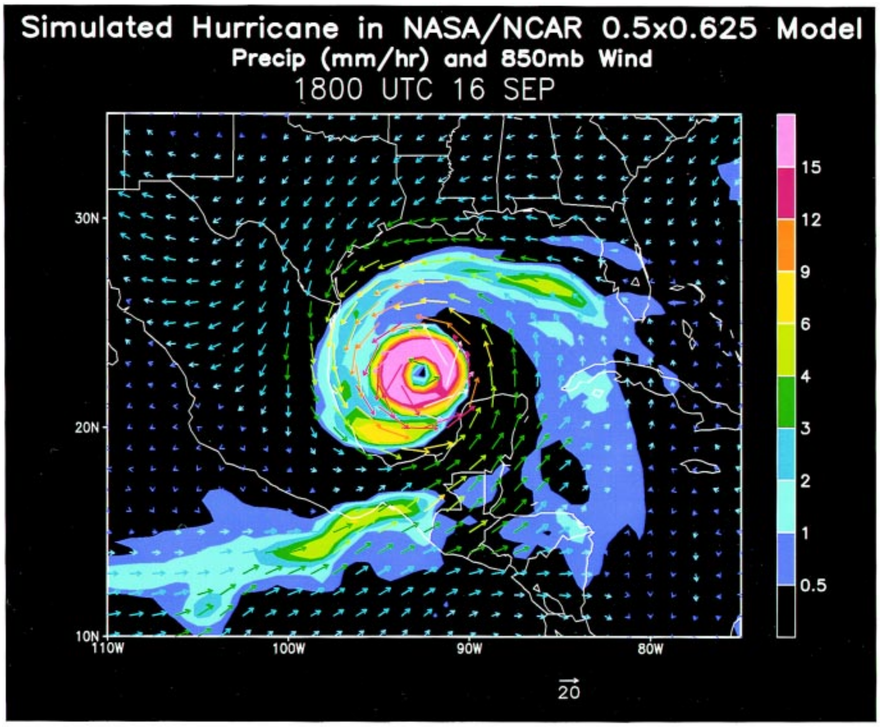

FIG. 10. Numerical simulation of an Atlantic hurricane realized by the NASA Data Assimilation Office, using a recent general circulation model developed in collaboration with the National Center for Atmospheric Research. This version of the model utilizes a 0.5° × 0.5° global grid, but nevertheless resolves the mesoscale structure of the hurricane and the central eye.

On still longer timescales, NASA supports a broad and diverse program of model studies, ranging from detailed simulations of selected climate processes (e.g., process-resolving cloud ensemble models) to model-based projections of potential global climate changes. The principal NASA climate modeling effort, based at the Goddard Institute for Space Studies (GISS), is leading the field in quantitative computation of the various radiative forcings factors that can influence global climate. GISS is now engaged in a detailed reexamination of physical and dynamical process representations in climate models, from turbulent mixing to sea-ice physics and land surface hydrology. Because of the chaotic nature of climate dynamics, any long-term climate prediction must be based not on just one, but a number of parallel model runs, in order to quantify the random uncertainty associated with natural variability. GISS is producing such "ensemble forecasts" to explore the range of natural climate variations and assess the degree of confidence in the outcome of model predictions.

Beyond the immediate goal of demonstrating the capability to produce meaningful climate change projections, the scientific objective is to understand the dynamics of the coupled atmosphere–ocean–land system, and ultimately provide a basis for the development of earth system models embracing the full diversity of physical, chemical, and biological processes that govern climate, the global cycles of water, carbon, and other nutrients, and the chemical composition of the earth atmosphere and oceans.

NASA recognizes this agenda requires considerable investments in supercomputer equipment and software engineering that can fulfill the computing needs for advanced earth system models, detailed representation of relevant processes, and sufficient spatial resolution to resolve all important scales of natural variability. The NASA effort focuses on constructing a common Earth System Modeling Framework (ESMF). The ESMF is intended to enable the creation of next-generation earth system models and allow for a variety of plug-in components to operate interchangeably within these models. A current High Performance Computing and Communication program initiative will facilitate the joint definition of the ESMF by the earth system modeling community and the migration of their codes to this framework.

8. Conclusions

Constructing a coherent research program and selecting research priorities is a major challenge in a broad scientific domain that crosses over a number of different disciplines, each evoking many scientific questions. The special challenge faced by NASA is balancing the competing demands placed on its limited resources and addressing the critical scientific questions most relevant to national policy issues, while achieving optimal use of the agency's unique capabilities for global observation, data acquisition and analysis, and basic research. In the process of formulating this research strategy, NASA has been fortunate to receive the support of many scientific experts in the earth system science community, particularly the U.S. National Academy of Sciences and NASA's Earth System Science and Application Advisory Committee.

We have described here one component of NASA's cross-disciplinary global change research strategy, focused on physical climate science, climate prediction, and the study of consequences for weather hazards and water resources. Notwithstanding this disciplinary focus, NASA is convinced that the ultimate challenge of earth system science is to consolidate scientific findings in various disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land and biosphere system. No earth system science program is complete without such a synthesis. The hallmark of the NASA earth science program is indeed the integration of observations and models, and the verification of model predictions against observed phenomena. The "discipline of prediction and verification" advocated by the National Research Council is adopted by NASA as a tool for progress and a necessary condition to ensure that environmental research delivers reliable science-based answers to the questions posed by society.

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