CHAPTER 12 Observing and Monitoring the Climate System

CHAPTER CONTENTS

For each of six overarching goals, this chapter introduces objectives that provide products and milestones to be addressed in the coming decade based upon current knowledge.

Goal 1: Design, develop, deploy, integrate, and sustain observation components into a comprehensive system.

Goal 2: Accelerate the development and deployment of observing and monitoring elements needed for decision support.

Goal 3: Provide stewardship of the observing system.

Goal 4: Integrate modeling activities with the observing system.

Goal 5: Foster international cooperation to develop a complete global observing system.

Goal 6: Manage the observing system with an effective interagency structure.

The Global Change Research Act of 1990 specifically calls for "global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales," as well as "documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades." The program continues to respond to this call by following a strategy for the development and deployment of a global, integrated, and sustained observing system to address science requirements and decision support needs at appropriate accuracies and space and time resolutions.

The Climate Change Science Program (CCSP) strategy for observations and monitoring includes guiding principles, identification of priorities, and effective management of available resources. The purpose of this chapter is to describe how all the disparate observations described by the CCSP plan will be systematically organized and managed to improve our understanding of the climate system. The data management discussion that follows (see Chapter 13) describes the plan for archival and distribution of these data.

The CCSP observations and monitoring component seeks to address the following overarching question:

> ***How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society?***

The development of space-based and *in situ* global observing capabilities was a primary focus of the program's first decade. Several new Earth-observing satellites, *in situ* networks, reference sites, and process studies are now producing unprecedented high-quality data that have led to major new insights about the climate system. The observing system for the future will build upon this success. For the purposes of this document, surface-based remote-sensing observations, as well as aircraft or suborbital measurements—in addition to direct observations within the atmosphere, ocean, ice, or land—will be considered as *in situ* measurements, and any references to *in situ* measurement networks should be considered as applying to networks using these techniques wherever appropriate.

The challenge for the coming decade is to maintain current capabilities, implement new elements, make operational the elements that need to be sustained, and integrate these observations into a comprehensive

"Knowledge of the climate system and projections about the future climate are derived from fundamental physics and chemistry through models and observations of the atmosphere and the climate system. Climate models are built using the best scientific knowledge of the processes that operate within the climate system, which in turn are based on observations of these systems. A major limitation of these model forecasts for use around the world is the paucity of data available to evaluate the ability of coupled models to simulate important aspects of past climate. In addition, the observing system available today is a composite of observations that neither provide the information nor the continuity in the data needed to support measurements of climate variables. Therefore, above all, it is essential to ensure the existence of a long-term observing system that provides a more definitive observational foundation to evaluate decadal- to century-scale variability and change. This observing system must include observations of key state variables such as temperature, precipitation, humidity, pressure, clouds, sea ice and snow cover, sea level, sea surface temperature, carbon fluxes, and soil moisture. Additionally, more comprehensive regional measurements of greenhouse gases would provide critical information about their local and regional source strengths."

Climate Change Science: An Analysis of Some Key Questions (NRC, 2001a)

global system to address the objectives of the CCSP research elements and decision support activities. Fundamental questions about the climate system and societal benefits that can be addressed are described in Chapters 3 through 11; these provide the basis for the observing system design and implementation. Illustrative examples of CCSP observation needs and milestones that address the research questions are described in Appendix 12.2. In addition, the overall climate observing system must address the five basic integrating goals for CCSP outlined in the introductory chapter:

- Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change
- Improve quantification of the forces bringing about changes in the Earth's climate and related systems
- Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future
- Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes
- Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

A system that integrates atmospheric, oceanographic, terrestrial, cryospheric, and cross-cutting observations does not currently exist *per se*. However, many components are available. For example, the Global Climate Observing System (GCOS) is a fairly well documented but not completely implemented international approach that has components in place to satisfy some climate requirements (see GCOS, 2003). GCOS is intended to provide a focused set of observations from a subset of established measurement sites that are considered to have a sufficient climate history and spatial distribution. The system discussed here, however, goes beyond GCOS. CCSP has expanded the initial inventory of important climate observations (see Appendix 12.1) to encompass the needs of research on and applications to the global cycles of carbon, water, energy, and biogeochemical constituents; atmospheric composition; and changes in land use.

Building on the CCSP mission, the United States has also taken a leading role in fostering the development of a more broadly defined and integrated global observing system for all Earth parameters—for example, including geological as well as climate information. The United States hosted a ministerial-level Earth Observation Summit in July 2003, with participation by many developed and developing nations as well as many intergovernmental and international nongovernmental groups. This summit initiated a 10-year commitment to design, implement, and operate an expanded global observing system that builds on the major observational programs currently operated by the U.S. and many other governments and international organizations. CCSP agencies have provided the leadership, definition, and support for the Earth Observation Summit, and CCSP will closely integrate the U.S. observation and data management programs with the international programs launched at the summit.

The global observation system needed to fully implement CCSP includes the evolution of the observing capability provided through the U.S. Global Change Research Program (USGCRP) and the operationally oriented monitoring systems routinely provided by several federal agencies. The latter were never included as part of USGCRP, and may or may not be included as part of CCSP in budget inventories. In fact, as noted below, a critical issue associated with the implementation of the observing system for CCSP is the transitioning of research observations, typically made through USGCRP, into operations, not currently included as part of USGCRP (see Objective 1.3). Any consideration of budgets associated with global observations should be based on those for all the component programs, and not the historic USGCRP budget.

The basic elements of a global observing system must consist of:

- Routine and continuing measurements of selected variables, collected using established principles
- Shorter term exploratory observations carried out with satellites, process-oriented field campaigns with *in situ* techniques, and other, finite duration, research observations, collected using established principles
- A comprehensive and reliable distribution network and long-term archive
- Analysis and integration activities, including the use of four-dimensional (space, time) data assimilation and scientifically validated models.

These elements must be managed by an effective national entity, and coordinated at the international level. The management must have the capability to establish observing protocols, provide oversight, address deficiencies, and mobilize resources as required to maintain the integrity of the entire end-to-end system. A major challenge for CCSP in this decade will be the transition of many observation elements developed in a research mode to a sustained and operational environment [e.g., NASA research satellites to National Polar-orbiting Operational Environmental Satellite System (NPOESS) and some *in situ* networks]. The resulting global system must obviously engage many countries in a cooperative enterprise. Developing such a system presents a daunting challenge that must be met to provide essential information for decisionmakers.

In order to move toward a global observing system, CCSP will focus on six goals:

1) Design, develop, deploy, integrate, and sustain observation components into a comprehensive system
2) Accelerate the development and deployment of observing and monitoring elements needed for decision support
3) Provide stewardship of the observing system
4) Integrate modeling activities with the observing system
5) Foster international cooperation to develop a complete global observing system
6) Manage the observing system with an effective interagency structure.

Goal 1: Design, develop, deploy, integrate, and sustain observation components into a comprehensive system.

A system is the integration of interrelated, interacting, or interdependent components into a complex whole. The path to an overall observing system must address a number of key issues in addition to the observation components themselves, including the priorities for development, the implementation strategy, assessment, utilization, cooperation with other providers of environmental measurements, data management, international development, and system management. Some of these activities are considered in this goal, but others are of sufficient complexity that they are a goal unto themselves and are discussed later in this chapter.

Prioritization. Observing elements are in place within existing research and operational programs that partially fulfill the requirements for meeting these objectives. Other key sensors and observing networks still need to be developed and implemented. Priorities for these augmentations are required because resources are limited. The CCSP research element questions and decision support goals provide the basis for determining priorities. In CCSP implementation plans, the research and decision support elements will provide a link between research question or decision support goal, measurement requirements, and the observation elements that meet the requirements. The prioritization criteria include: benefit to society, scientific return, partnership opportunities, technology readiness, program balance, and implementation of the climate monitoring principles (see Appendix 12.4). The management of the program will recommend priorities in consultation with the scientific community using the management mechanisms outlined in Chapter 16.

Evaluation. A key lesson learned over the past decade is that observing systems and networks must be implemented in a way that allows

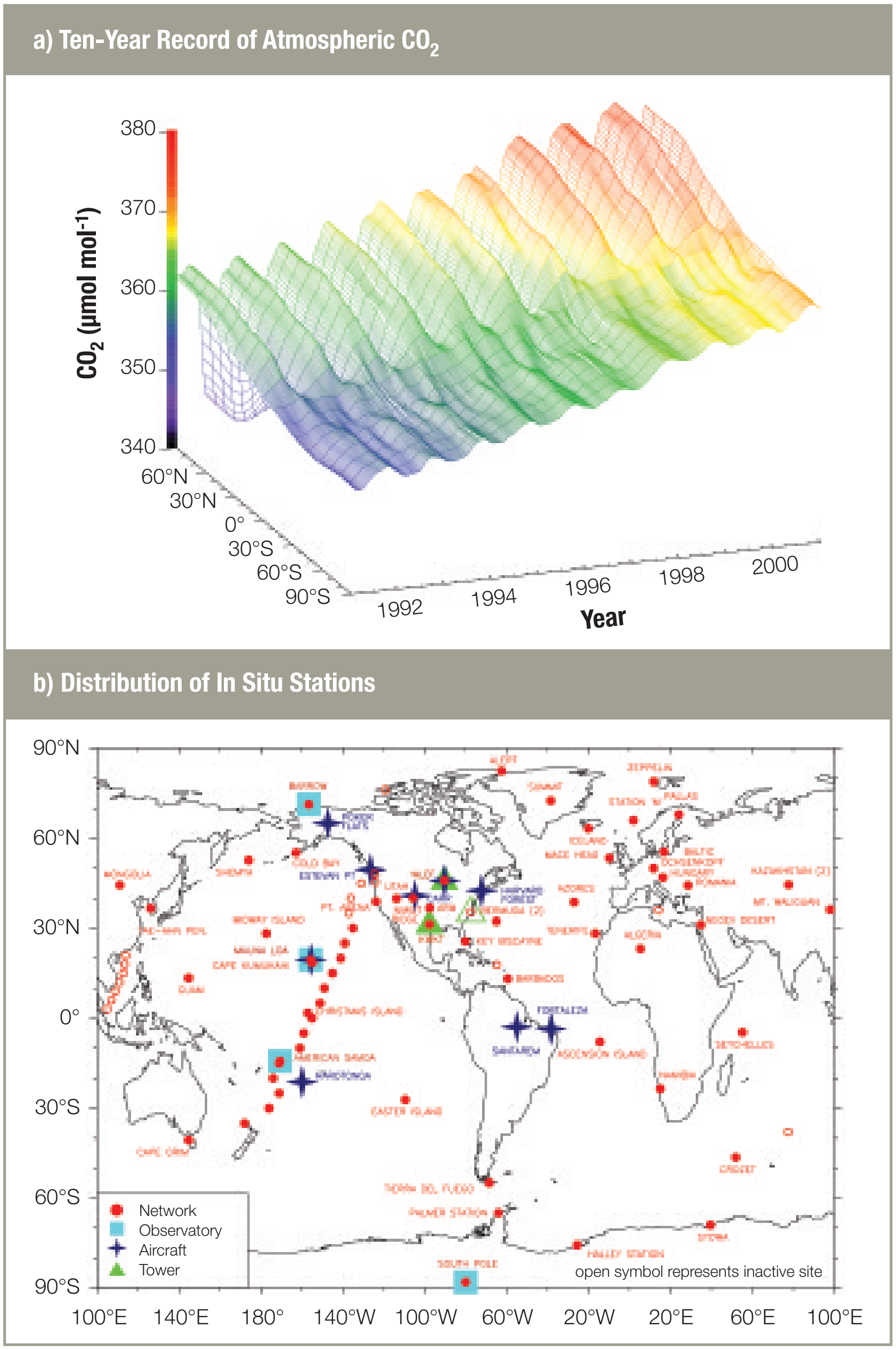

Figure 12-1: (a) Ten-year record of atmospheric carbon dioxide (CO_2) at a variety of stations as a function of latitude, and (b) distribution of *in situ* stations collecting data on CO_2 and other greenhouse gases. Source: Pieter Tans, NOAA CMDL. For more information, see Annex C.

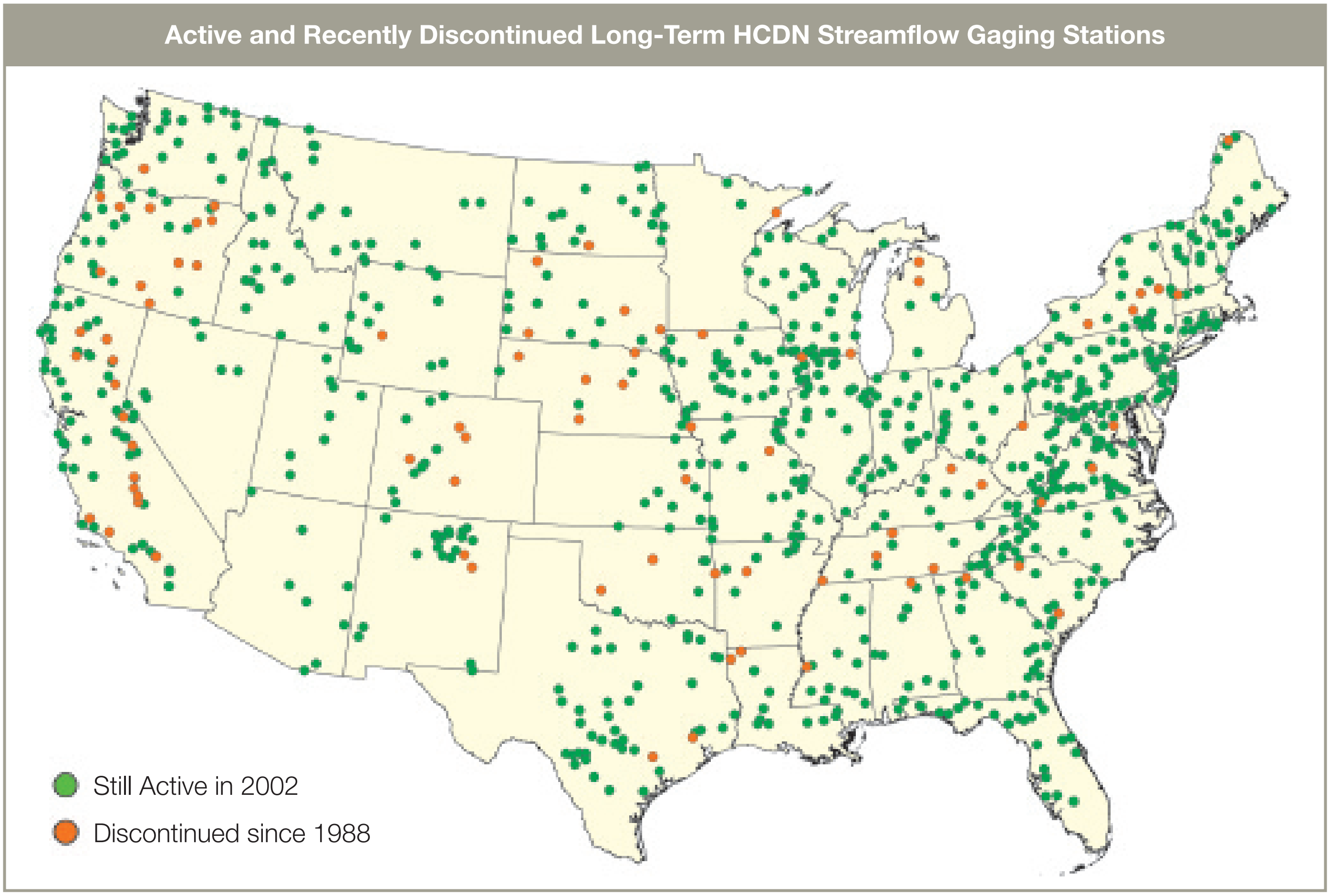

Figure 12-2: The U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN) was compiled in 1988 and included 854 gauges that were active and had at least 36 years of record. Stations that are still active are shown in green. Stations discontinued since 1988 are shown in red. These stations would have had at least 50 years of record as of 2002, if they had been kept in operation. Source: William Kirby, Global Hydroclimatology Program, USGS. For more information, see Annex C.

flexibility as both requirements and technology evolve. Therefore, the program will regularly assess the science and decision support requirements and propose modifications to the observing systems required for CCSP to execute its research plans. This process will involve the scientific community and program managers working on each research element, as well as those involved in modeling, scientific assessment, and other integrative activities (see Goal 6).

Cooperation. Many important observing systems are developed and operated by organizations that are not formal participants in CCSP, making the development of strong cooperative relationships that extend beyond the current CCSP a necessity. CCSP will work with observing system partners and the scientific community to identify climate requirements for these observing systems and to set priorities in light of available resources and competing needs.

Objective 1.1: Develop a requirements-based design for the climate observing system

A requirements-based design will be developed to identify baseline and minimum requirements that will address CCSP research element questions and decision support goals. U.S. needs and contributions will be weighed in the global context of the requirements and contributions of other nations and coordinated with them in a manner that will lead to a global system. The most efficient and effective observation elements and networks will be selected that will meet the requirements.

Objective 1.2: Stabilize and extend existing observational capabilities

CCSP will maintain and improve basic research observing facilities, networks, and systems (both space-based and *in situ*). Climate-quality data requires long-term continuous records (see Chapter 4, Figure 4-1). It is critical to maintain records required to answer research questions before they are lost for other reasons (see Figure 12-2). Long-term observations require a focus on maintenance and replacement to sustain the capability at a sufficient level of accuracy to detect climate change over decades. To meet this objective, CCSP will:

- Continue satellite missions (see Figure 12-3) that are critical to answering the research element questions and upgrade the quality of their data to climate standards
- Extend and stabilize *in situ* networks for global coverage with consistent data quality, including moored, drifting, and ship-based networks in the ocean; surface and upper air networks in the atmosphere; and the major terrestrial networks
- Provide a uniform global set of surface reference sites of key ocean, land, atmosphere, and hydrology variables [see Figure 12-1 as an example of a global system for carbon dioxide (CO_2)]

- Provide careful calibration and overlapping operation of new and old technology during transitions to maintain quality control of data records
- Extend the capacity in terrestrial inventory programs to provide comprehensive information for key ecosystems within the United States.

Objective 1.3: Develop and implement a strategy for the transition of proven capabilities to an operational mode

The transition of proven research observation elements to sustained or operational status will make these components more cost-effective and sustainable for long-term benefit. CCSP will work toward an effective integration for the planning and development of research and operational systems. CCSP will develop a strategy to transition from research to operations that will adhere to the climate monitoring principles (see Appendix 12.4), including continuity, in order to have the most benefit to its objectives. Management structures will be developed to provide for a handoff from research management to operational systems management. The operation management will be responsible for continuing the research mission and producing and delivering day-to-day operational results and products.

Objective 1.4: Incorporate climate and global change observing requirements in operational programs at the appropriate level

Operational observation networks continue to be the backbone of climate system measurements. These networks, with only modest incremental costs, will satisfy significant parts of the climate observing requirements as described in the climate monitoring principles (see Appendix 12.4). Scientific, as well as decision support, oversight of operational systems for climate must be implemented using the concept of Climate Data Science Teams described in Goal 6 below.

Objective 1.5: Identify, develop, and implement measurement improvements

CCSP must maintain a sustained research and technology development program to address major deficiencies in observing systems and the paleoclimate record identified in Chapters 3 to 9 (e.g., closing the budgets for carbon, energy, and water cycles; integrating the coastal ocean monitoring systems; and completing records about decadal- and century-scale climate variability prior to the instrumental record). To the extent possible, new or improved measurements will be integrated into existing networks so as to minimize redundant operations and costs. Future global measurements from satellites and regional *in situ* networks will be developed that dramatically improve quality and vertical, spatial, and/or temporal resolution, especially to enhance regional coverage for decision support applications.

Objective 1.6: Continue intensive field missions

The science chapters have described and justified numerous field studies that integrate airborne (*in situ*), surface, and satellite observations over regional scales and durations from days to several weeks. These intensive observation periods provide valuable data for

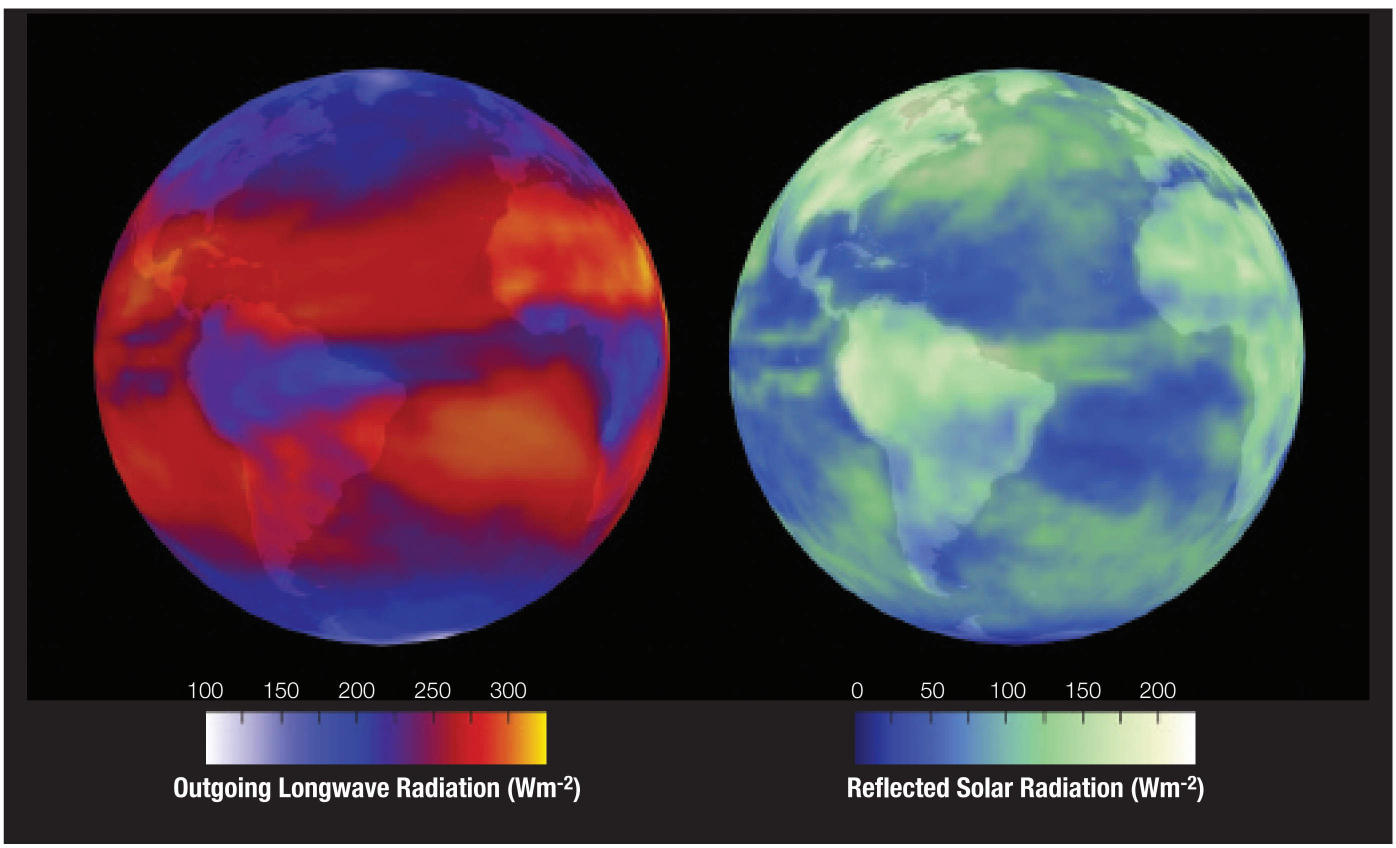

Figure 12-3: For scientists to understand climate, they must also determine what drives the changes within the Earth's radiation balance. From March 2000 to May 2001, the Clouds and Earth's Radiant Energy System (CERES) satellite measured some of these changes and produced new images that dynamically show heat (thermal radiation) emitted to space from Earth's surface and atmosphere (left sphere) and sunlight reflected back to space by the ocean, land, aerosols, and clouds (right sphere). Source: CERES Project, NASA (<http://asd-www.larc.nasa.gov/ceres/ASDceres.html>).

testing and validating satellite retrieval algorithms, and for the fine-scale resolution necessary to test, validate, and constrain physical processes in climate models. These coordinated observation efforts will need to become even more sophisticated as satellites evolve towards formation flying, onboard processing, and smart sensor technology. Aircraft remain a valuable platform for CCSP and mechanisms to make efficient use of these facilities across the CCSP agencies will be investigated.

Objective 1.7: Assess observing system performance with uniform monitoring tools and evaluation standards

A global effort of this magnitude must be managed as a system in order to be effective. For agencies to assess the performance of the observing system, an institutional mechanism must be put in place to monitor the status of the globally distributed components and to evaluate their combined capabilities.

CCSP, working with international partners, will develop a system architecture for monitoring distributed global operations that establishes and maintains links among the *in situ* and satellite elements and the data and modeling activities that are essential components of climate observation. The purpose is to provide a framework so that the nation can manage its observing system more efficiently and effectively, and:

- Provide an integrated view of the observing system linked to the CCSP mission
- Develop a more cost-effective observation system
- Allow all observations to be accessible by all customers when needed
- Provide a framework for examining future requirements and costs
- Allow for evolutionary improvements
- Identify gaps and overlaps
- Identify opportunities to migrate observations from the research elements into a sustained operational status.

The guiding principles for development of this uniform interagency and international monitoring capability include:

- Provide a system that is requirements-based
- Provide elements that are standards-based and interoperable
- Provide for system evolution that is minimally intrusive to other national and international missions
- Provide ample margins to accommodate changing requirements
- Provide a basis for continual evaluation and evolution.

Objective 1.8: Generate climate information through analysis and assimilation

Many countries have gathered climate system data to document climate system variability using many different instrument types during the past 150 years. In order to document and understand change from a historical perspective, we need to develop global, comprehensive, integrated, quality-controlled databases of climate system variables based on historical or modern measurements, and provide the user community with open and easy access to these databases. We must integrate these records as far into the past as is practical to reduce uncertainties in the climate trend estimates of individual parameters.

Our understanding of some of the changes in the physical climate system over the past 50 or more years has improved because of systematic reprocessing and integration of climate observations using state-of-the-art climate models and data assimilation technology. This must be continued through a routine and iterative improvement process that incorporates a rigorous research and validation component.

Objective 1.9: Initiate or participate in end-to-end pilot demonstrations of atmosphere, ocean, and terrestrial hydrologic observing systems

The integration of satellite and *in situ* observing networks for synthesis of the ocean, atmosphere, or terrestrial spheres in a systematic manner will be addressed through focused pilot programs. The Global Ocean Data Assimilation Experiment, while not specifically focused on climate issues, is an example of a pilot approach to the synthesis of ocean observations.

Objective 1.10: Develop a requirements-based program for collecting, integrating, and analyzing social, economic, and health factors with environmental change

Across the range of research on human response and consequences to climate change there is a particularly strong need for the integration of social, economic, and health data with environmental data (see Chapter 9). Observations will be used to address gaps in understanding, modeling, and quantifying the sensitivity and vulnerability of human systems to global change and measuring the capacity of human systems. Using retrospective analyses of consequences of shifts in climate will also help model future ability of hazard and resource management institutions to respond.

Goal 2: Accelerate the development and deployment of observing and monitoring elements needed for decision support.

CCSP provides resources to develop observation systems and processing and support systems that will lead to reliable and useful products. These products will provide critical policy-neutral information for decision support and policymakers in areas such as climate and weather forecasting, human health, energy, environmental monitoring, greenhouse gases, and natural resource management.

CCSP will enhance the existing long-term monitoring elements with accelerated focused initiatives to provide a more definitive observational foundation for determining the current state of the climate. Many shortcomings of the current climate observing system relate to understanding climate forcings. In addition, fundamental observations for characterizing and understanding the state of the climate are needed for the global ocean, atmosphere, land surface, and ice variables. For the atmosphere, only half of the GCOS Upper-Air Network (GUAN), established for climate purposes, has been reporting regularly, and the GCOS Surface Network (GSN) for climate has had similarly disappointing results. The ocean is poorly observed below the surface, which limits our understanding about the ocean's response to a warming planet and its ability to naturally sequester greenhouse gases. Over land, the spatial heterogeneity requires detailed measurements and presents a major challenge.

In the budget requests for the past 2 years (FY2003 and FY2004), progress has been made to address many of these deficiencies, as described in Appendix 12.3. The objectives in this goal outline specific CCSP elements that will expand on this progress and support a directed strategy to focus resources and accelerate observations for climate change and decision support.

Objective 2.1: Complete the required atmosphere and ocean observation elements needed for a physical climate observing system

Within the climate monitoring arena, atmosphere and ocean observation elements to measure the physical aspects of the climate system are the most complete, and are ready to be brought together as a system. For example, the detailed open ocean observing system has been designed at both national and international levels through numerous community workshops, and implementation is about 40% complete (see Figure 12-4). The atmospheric system, which is a mixture of both climate and non-climate elements, has been recently examined (GCOS, 2003) and needs support for fixing degradations, sustaining current capabilities, and adding improvements. An accelerated effort to complete these two subsystems will improve understanding of climate characterization, forcing, and prediction, as well as facilitate the implementation and testing of the interagency management of complete observing systems. Focused new data management practices are being developed and will promote efficient acquisition, validation, delivery, and archival of the measurements and data products. In order to complete these systems the following steps need to be taken in conjunction with international partners:

- GSN measures surface temperature, pressure, and precipitation at about 1,000 sites within the World Weather Watch (WWW) surface climate network. The network is not providing useful data at many sites in underdeveloped countries because of a lack of resources and training. Furthermore, only one-third of the network has provided historical data for examining climate extremes. CCSP will improve GSN data reporting.
- GUAN collects upper atmosphere temperature, wind, and humidity at 150 stations around the world. Performance at about one-third of the stations is poor. CCSP will improve *in situ* atmospheric column observations in GUAN. In addition, CCSP will identify techniques and implementation strategies for *in situ* atmospheric column observations of temperature, wind, and water vapor over the ocean, where GUAN cannot be used.
- CCSP will complete the U.S. Climate Reference Network of 250 stations nationwide to provide long-term homogeneous observations of temperature and precipitation that can be coupled to past long-term observations for the detection and attribution of present and future climate change.

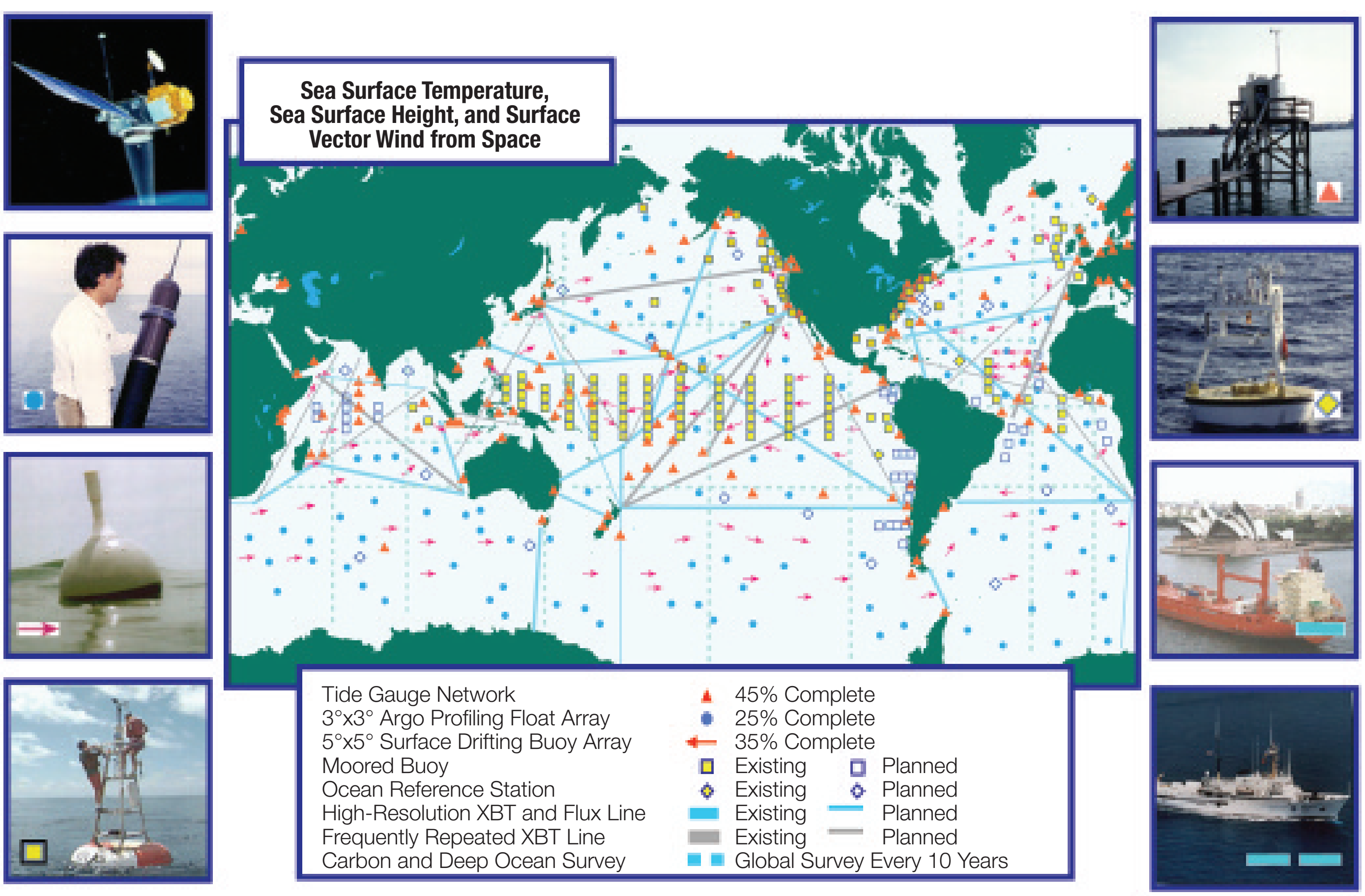

Figure 12-4: In 2003, the international global ocean observing system for measurements of the physical climate system was 40% complete. Source: Michael Johnson, NOAA Office of Global Programs.

- The United States will increase contributions to monitoring upper-ocean temperature and salinity structure that will improve understanding of the ocean's response to a warming planet. CCSP will support 50% of the international ocean profiling float program (Argo) and additional expendable bathythermographs from ships-of-opportunity to observe changes in heat and freshwater content.
- CCSP will improve estimates of global sea surface temperature for climate model initialization for better prediction capability, as well as regional barometric pressure and surface current velocity for improved model validation, by completing the global distribution of 1,250 surface drifting buoys.
- CCSP will reduce uncertainty in sea-level rise estimates by obtaining absolute positions for sea-level stations that are required to improve the calibration of satellite altimeters, used for the detection of long-term sea-level trends.
- The United States will continue to monitor the state of the tropical atmosphere and oceans in the Pacific and Atlantic Oceans with instrumented moored buoys and satellites, and contribute to the development of a similar network in the Indian Ocean for improved climate prediction and research.
- CCSP will improve model-based global air-sea flux estimates with surface flux reference moored buoy sites and Volunteer Observing Ships (also collect routine surface meteorological observations) with upgraded instruments for climate-quality observations.

Objective 2.2: Retrieve important paleoclimate records to provide a global long-term perspective on historical changes in climate

There are three aspects of the paleoclimatic record that need to be addressed by accelerated and focused programs within CCSP in order to improve characterization of long-term climate change and provide a valuable benchmark for testing models that are used to project the future (see Goal 4):

- Increase priority for retrieving rapidly disappearing paleoclimate information (e.g., melting glaciers, loss of corals and trees whose growth patterns are used for dating purposes, etc.) before these records are permanently lost
- Accelerate efforts to obtain interannual climate information in the Southern Hemisphere and tropics to develop a global record of millennium-scale climate variability
- Improve the integration of paleoclimatic observations and measurements with historical and modern climate data to form continuous time series of climatic information.

Objective 2.3: Develop new capabilities for ecosystem observations

Changes in an environmental variable—most often warming, but also changes in precipitation and air quality—have often been related to observed changes in biological and ecological systems. Several examples were mentioned in the Working Group II contribution to the Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC, 2001b), including thawing of permafrost, lengthening of the period of active photosynthesis in mid- and high-latitude ecosystems, poleward shifts of plant and animal species ranges, movement of plant and animal species up elevation gradients, earlier spring flowering of trees, earlier spring emergence of insects, earlier egg-laying in birds, and shifts in a forest-woodland ecotone (the boundary between the forest and the woodland).

These changes in ecosystems and organisms are consistent with warming and changes in precipitation, but the possibility remains that the observed biological and ecological changes were caused (in part) by other factors such as biological invasions or human land and marine resource management. Because of this, the attribution of the causes of biological and ecological changes to climatic change or variability is extremely difficult. Moreover, because many ecosystem-environment interactions play out over long periods—ultimately involving evolutionary changes and adaptations within ecosystems—long periods of study are needed in many cases to draw firm conclusions about relationships between environmental change, effects of that change on biological and ecological systems, and the significance of any observed biological or ecological changes for the functioning of ecosystems (see Chapter 8).

New research is needed to provide a significantly more complete picture of how biological and ecological systems may have responded to recent climatic change and variability, including possible biological or ecological responses to extreme events. New observational systems will also be needed to appropriately monitor potential future changes in the environment and accompanying biological or ecological changes (if any). A key challenge will be to provide organization, guidance, and synthesis for the emerging field of observed effects of climate change on biological and ecological systems.

CCSP will initiate studies of early effects and indicator systems across diverse ecosystems and geographic regions. A substantial amount of existing climate and effects data, a variety of monitoring efforts, and comparisons to scenario-based effects studies can be marshaled in this effort. CCSP will facilitate linked analyses of climatic trends and observed biological and ecological effects by supporting identification of appropriate past and ongoing monitoring efforts, design of needed new monitoring systems, and synthesis of results across ecosystems and regions. Research efforts will target those ecosystems that are subjected to the most rapid or extensive environmental changes and/or are most sensitive to possible environmental changes.

Long-term, spatially explicit, and quantitative observations of ecosystem state variables and concomitant environmental variables are needed. Initial activities and products will include:

- Define ecosystems sensitive to climate change and thresholds for measurable impacts
- Identify ecosystems and the interfaces between ecosystems (ecotones) that are either sensitive or resilient to environmental change
- Identify ecosystems experiencing the most rapid environmental changes (e.g., ecosystems located at high latitudes and high elevations or coastal ecosystems affected by ongoing sea-level rise and intensive human influences)
- Identify concurrent trends in other factors, such as population and land-use change and provide links to data sets that document these trends
- Identify links to biological and ecological data sets from monitoring programs, including those from remote-sensing platforms

- Validate impacts studies done with climate change scenarios over the near term or for small amounts of warming using observed climate and impact data
- Develop observational design criteria related to risk assessment and identification of causes of changes in distribution of pests and pathogens (e.g., climatic change interacting with weather)

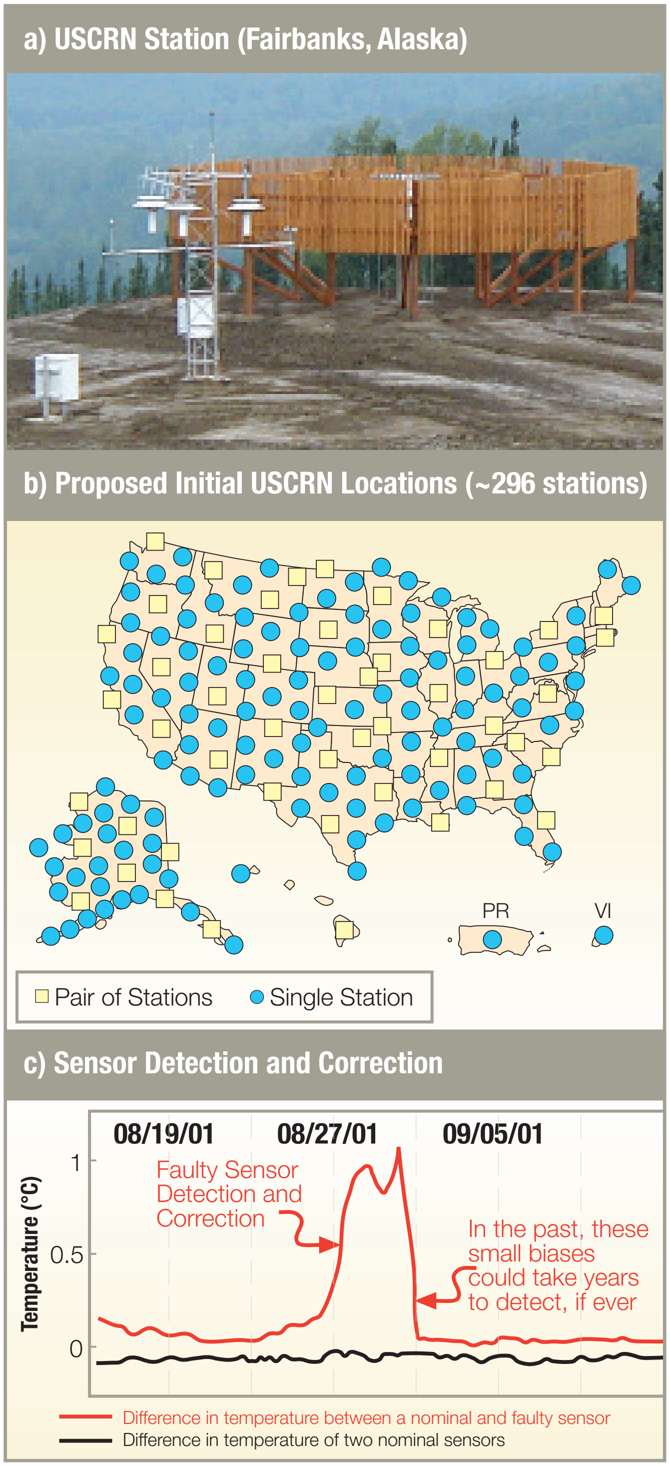

Figure 12-5: The U.S. Climate Reference Network is being established to reduce uncertainty and biases in long-term trends of key atmospheric variables at 296 stations (a&b). The monitoring system is designed such that multiple independent measurements are being made to capture sensor drift or biases (c). Source: NOAA National Climate Data Center.

- Develop design criteria for remote and *in situ* observations of biological and ecological systems that will help determine whether any observed ecological changes are attributable to global change
- Produce global, synoptic observational data products from satellite remote sensing documenting changes in biomass, albedo, leaf area and duration, and terrestrial and marine ecosystem composition for use in geographic information system (GIS)-based decision support systems
- Produce climate data at appropriate temporal and spatial scales for impacts studies.

Objective 2.4: Provide regular reports documenting the present state of the climate system components

CCSP will initiate a regular reporting program on the state of the climate system. Reports on various components of the system will highlight analysis products from the observing system to address the overarching question stated at the beginning of the chapter:

- Provide regular *State of the Climate* reports that include analyses of trends and variability in climate throughout the historical record using instrumental and paleoclimate records
- Evaluate the capabilities of existing and planned observing networks for providing data that will support the analysis of changes and trends in climate extremes and hazards
- Calculate the number of Climate Reference Network observing sites required to reduce the uncertainty in the observed climate signal for surface temperature to less than 0.1°C per century and precipitation to less than 1% per century on national and regional scales (see Figure 12-5)
- Regular reports evaluating the reduction in time-dependent biases in the space-based observing system obtained through implementation of the GCOS satellite monitoring principles and scientific data stewardship including the development of complementary independent observation and analysis techniques for critical climate variables
- For all operational monitoring networks, develop the tools necessary to identify time-dependent biases in the data as close to real-time as possible
- For climate monitoring networks, develop an operational system to identify non-climatic biases in the observing system for those climate system variables identified by the NRC (1999g) report on the adequacy of climate observing systems as relevant to detection, attribution, and direct societal impacts
- Identify and quantify the source of biases in climate system variables in existing climate reference data sets.

Goal 3: Provide stewardship of the observing system.

Observations of the climate require careful scientific oversight because climate signals are usually quite small relative to higher frequency phenomena in the data. Consequently, the climate science community has developed a set of principles that can be uniformly applied to all relevant measurements. In addition, special rigor must be applied to the algorithms, which are used to translate fundamental physical measurements into useful geophysical products,so that consistent results can be obtained and improved. Finally, scientific oversight of the algorithm, instrument calibration, and data processing and validation is critical to understanding the differences between instrument error and climate signal, and reduction of the error bars that define the uncertainty. This approach is captured in the four objectives of this goal.

Objective 3.1: Follow climate monitoring principles

Efforts in the last decade to use current research and operational data sets in global climate change research have provided a critical set of lessons learned. These lessons have been gathered into two sets of climate monitoring principles (see Appendix 12.4). These principles and experience will be used to guide the major improvements needed for the observing system. Instrument calibration, characterization, and stability become paramount considerations. Instruments must be tied to national and international standards such as those provided by the National Institute of Standards and Technology (NIST). When observations cannot achieve sufficient absolute accuracy or changes in spatial or temporal sampling occur, overlapping observations with high stability are required to ensure accurate monitoring of global change. Agreed-upon measurement protocols and procedures (e.g., continuous data validation and intercomparisons) are required to produce climate-quality data.

Objective 3.2: Provide independent measurement and analysis

To be policy-relevant, climate data must have reliable confidence intervals. Narrow intervals are most effective for decision support and policy development. Experience from previous scientific assessments, NIST, and other national standards laboratories have shown that actual accuracy is only known after comparison of independent measurements and analysis from multiple laboratories. Most climate observing systems are pushing the edge of capability in calibration. This suggests a final climate observing principle that climate observations should strive to address: *Each key climate variable will be measured using independent observations and examined with independent data analyses.*

Observation independence verifies instrument accuracy, while analysis independence verifies algorithms and computer code. For sea surface temperatures, examples of independent observations include satellite-derived measurements via infrared [Advanced Very High-Resolution Radiometer (AVHRR)] and passive microwave [Advanced Microwave Scanning Radiometer (AMSR)], and *in situ* instruments on ships, buoys, and floats. But many climate variables do not yet have independent sources. When surprises in climate data sets occur relative to current theory, independent confirmation is essential to ensure policy-relevant confidence in the results. A recent key example of this need is the air temperature record from radiosondes and the Microwave Sounding Unit (MSU) satellite data, as well as the different results from two analyses of the MSU satellite record. Using a single measurement of a key climate variable is a high-risk approach to reducing uncertainty for policymaking decisions.

Objective 3.3: Provide a sound foundation for climate-quality data products that will maintain integrity over time using well-characterized sensors and validated algorithms

An instrument radiometric mathematical model, termed the "measurement equation" by metrology experts, is developed to define, describe, and represent the relationship between the sensor output and desired physical observable (e.g., volts to temperature, counts to radiance, etc.). Additional models are used to reference the results in space and time (geo-location), and, finally, models are used to derive desired physical parameters (ozone profile, chlorophyll concentration, etc.). This process of characterization has been very successful in the past, especially for satellite programs. Its practice will continue to be encouraged, the results promulgated, and the instrument designs critically evaluated so that future measurements will produce the desired results.

It is important to understand that a sensor does not have to be ideal, but it must be well-characterized so that systematic effects can be evaluated and removed, even years after the mission, if new effects are identified. If these data are not available, the utility of the measurements is greatly compromised. The measurement equation approach defines the problem and places the entire procedure on a scientific basis. In the future all climate-quality observations need to be linked to their climate data records through an approved algorithm model that is described, for example, in an algorithm theoretical basis document (ATBD). These documents were pioneered by NASA in its implementation of the Earth Observing System (EOS) and provide a valuable lesson learned for future measurements.

Objective 3.4: Scientific stewardship for production of climate data records

Achieving climate accuracy with global and decadal sampling represents a unique scientific and organizational challenge. Calibration and stability requirements for climate data are often an order of magnitude more stringent than weather data. This accuracy is often achieved in research *in situ* and satellite data sets, with the length of this accuracy being dependent on the lifetime of the platforms and rate of instrument degradation; while in the longest satellite case (Earth Radiation Budget Satellite) this may approach 2 decades, in other cases it is much shorter. Global decadal sampling is often achieved in operational data sets, but without the accuracy and stability. Scientific data stewardship addresses this challenge through the production of Climate Data Records (CDRs).

Ultimately, the production of CDRs includes setting climate accuracy and stability requirements, instrument calibration and characterization, algorithm selection and development, end-to-end data validation and error analysis, quality control, and data production. Long-term archival and effective distribution are also essential and are addressed in Chapter 13. Experience in the last decade has shown that achieving CDR stewardship requires active and continual collaboration with the science community including both data producers and data users. Examples include Atmospheric Radiation Measurement (ARM) and Aeronet surface observations, the global surface temperature record, Tropical Atmosphere-Ocean buoys, and many forms of satellite observations for ocean, land, and atmosphere climate variables. Climate Data Science Teams (CDSTs) will be discussed in Goal 6 as a critical implementation strategy for the climate observing system.

Long-term CDRs will come about through the harmonious integration of highly accurate, research-quality observing systems with longer term operational and paleoclimate data. To reach the desired level of climate quality will also require additional efforts for current operational systems. We anticipate that CDSTs will be required to produce climate-quality data and represent the organizational link that provides operational level continuity with research-quality science direction.

The stewardship of scientific data is required to produce the climate-quality data sets that are a critical resource for policymakers and a legacy for future generations. As the length of CDRs increase, the power of the data to narrow uncertainties will increase and provide a basis for future decisions.

Goal 4: Integrate modeling activities with the observing system.

There are two primary roles for observations in the improvement of climate models: evaluation and initialization. At the same time, climate system models provide important insights for the improvement and interpretation of measurements through the use of simulations. These two-way interactions of observations and models affect not only the design but also the improvement of the observing system.

Objective 4.1: Develop protocols to evaluate models with climate-quality observations

Model testing uses observations to determine the uncertainties in current climate models and to prioritize needed improvements in future models. This is the most critical function of climate data records and depends primarily on two factors: (1) accuracy and stability of the climate data; and (2) the intrinsic background variability or noise in the Earth's climate system. Both factors vary with temporal and spatial scale. Climate system noise is typically largest at short time scales and small spatial scales (e.g., seasonal/regional scales), and smallest at long time scales and large spatial scales (e.g., century/global scales). Useful climate model tests require that both the data accuracy and the climate system noise be carefully assessed. As a result, climate accuracy requirements cannot be specified as a single number per variable, but must also be defined at several relevant temporal and spatial scales. Examples of relevant temporal/spatial scales include monthly/local, seasonal/regional, annual/zonal, and decadal/global. Some climate data records will have sufficient accuracy or stability to resolve regional climate change but inadequate coverage to resolve global changes and *vice versa*.

Consequently, observations and models of the climate system cannot make progress without continuous interaction between and understanding of the uncertainties in each research area (see also Chapter 10, Objective 1.3). Rapid progress requires regular interaction between the modeling and observation communities through CDSTs. One of the most critical collaborations between climate model and measurement scientists in the future will be the definition of prediction accuracy metrics capable of constraining key model uncertainties, such as cloud and water vapor feedback. Currently, such metrics are rather ad hoc because of the difficulty in unraveling the complex nonlinear climate system and in documenting climate data accuracy as a function of time and space. In the simplest sense, how would you recognize a perfect climate model if you had one? What tests would it pass? How will we know when the observing network is sufficient to characterize, attribute, and predict climate changes accurately? The answers are a function of both climate models and the climate observing system design.

The definition of climate model evaluation metrics will affect observing system design. As models and data improve in quality, these metrics will evolve in an iterative fashion over the next decade.

Objective 4.2: Use observations to initialize climate variability models

Climate model initialization is primarily effective only for seasonal-to-interannual time scales, and for initialization of the state of the world's oceans, soil moisture, and vegetation. These latter conditions reflect climate processes with sufficiently long time scales that their initial state can affect seasonal-to-interannual climate states. The prime initialization example is prediction of El Niño events using initial ocean conditions. To improve short-term climate forecasts, it will require new and improved technologies in data assimilation and better utilization of *in situ* and remotely sensed global ocean, atmosphere, and terrestrial observations of key physical variables, such as ongoing observations of temperature and new measurements of salinity and soil moisture (see Chapter 10, Objective 1.4).

Objective 4.3: Utilize climate system models to assist in the design of observation systems

While climate models are not perfect, for some variables they can strongly support the estimation of accuracy requirements for CDRs. Consider the following simple paradigm of climate change: **forcing** => **feedback** => **response** => **climate change**. If the Earth were such a simple linear system, then designing observing systems and testing climate model predictions would be a relatively straightforward process. But the climate system is highly coupled and fundamentally nonlinear. Consequently, intrinsic internal variability is an inherent part of the real climate system. Climate change must be detected and understood. However, this signal is usually smaller than the background climate variability (e.g., year-to-year climate variability). CDRs will require accuracies at a temporal and spatial scale greatly below the level of natural variability.

Unfortunately, most quantitative observations of the climate system only exist for the last century and are a combination of background and climate variability, climate change, and observation error. Using the total variability of the system to define measurement requirements represents only an upper limit on required accuracy and is not likely to be sufficient. Climate model simulations, on the other hand, do not include the full complexity of the Earth's climate system. The models typically represent an underestimate of background variability. As a result, climate model ensemble simulations can be used to estimate the required accuracy for the observation system. The ensembles can also specify intrinsic variability of the system as a function of temporal and spatial scale. These simulations can use varying climate forcing and can separate background variability from the climate signal by running large numbers of simulations with slightly varying initial conditions, but the same boundary conditions.

Objective 4.4: Develop protocols for validating data assimilation and reanalysis products from the observing system

Increasingly, global and regional data sets derived from data assimilation models and retrospective reanalysis models are being used for climate research, monitoring (time series), diagnostics, applications, and impact assessments (see Objective 1.8 and also Chapter 10, Objective 1.5). Evaluation protocols must be developed to assess the accuracy and stability of these reanalysis products for climate applications. Acceptable error standards need to be established that will provide guidance on whether the data sets are usable or not, especially at regional scales and for model-derived/computed parameters.

Goal 5: Foster international cooperation to develop a complete global observing system.

The range of global observations needed to understand and monitor climate processes, and to assess human impacts, exceeds the capability of any one country. Cooperation is therefore necessary to address priorities without duplication or omission (see Chapter 15). Satellite missions and *in situ* networks require many years of planning. Observations of the state of and trends in planetary processes cut across land, water, air, and oceans. National programs need to fit into larger international frameworks. At the international level, participation in both science and operational oversight committees must be continued, and strengthened or developed in disciplines that have not yet developed a global system.

In 1998, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) noted with concern the mounting evidence of a decline in the global observing capability and urged Parties to undertake programs of systematic observations and to strengthen their capability in the collection, exchange, and utilization of environmental data and information. The United States supports the need to improve global observing systems for climate, and will join other Parties in submitting information on national plans and programs that contribute to the global observing capability.

Objective 5.1: Foster and support international partnerships in observations

The United States is an active and leading partner in the development and support of a global observing system that assembles key elements from a number of observing networks under the aegis of appropriate international organizations. With regard to climate, GCOS has fostered the integration of key elements including meteorological observations from the WWW Global Observing System, atmospheric constituents from the Global Atmosphere Watch, hydrological observations from the World Hydrological Observing System, critical oceanographic climate variables from the Global Ocean Observing System (GOOS), and several terrestrial variables from the Global Terrestrial Observing System (GTOS). Coordination of global satellite observations is carried out through the Committee on Earth Observation Satellites (CEOS). This is particularly important as multi-national, multi-spacecraft constellations and increased use of higher altitude orbits (e.g., geostationary) are used to improve the temporal resolution of global observations that may further enhance decision support.

Given the importance of validating satellite observations under a broad range of geophysical and biogeochemical conditions, participation of international partners—in providing coincident and correlative information that can be used to test and improve satellite observations—is especially important. International partners are also important in the implementation of field campaigns that are best carried out with the full scientific involvement and logistical support of the host countries.

The full implementation of a global system for climate will require enhanced international coordination and commitment. Components for atmospheric, oceanic, terrestrial, and satellite observations are supported at varying levels depending on scientific priorities, availability of national contributions, and the sophistication of the relevant observing technologies. A specific focus on climate variables is essential to provide an adequate database to meet climate needs.

Recently, these observing systems, their sponsors, and the satellite community have developed the International Global Observing Strategy (IGOS). IGOS is a strategic planning process, uniting the major satellite and surface-based systems for global environmental observations of the atmosphere, oceans, and land in a framework for decisions and resource allocations by individual partners. The IGOS Partnership (IGOS-P) focuses specifically on the observing dimension in the process of providing environmental information for decisionmaking. This includes all forms of data collection concerning the physical, chemical, and biological environments of our planet, as well as data on the human environment, pressures on the natural environment, and environmental impacts on human well-being. IGOS-P is currently focusing on identifying and gaining commitments for essential requirements for observing oceanic processes, global carbon, atmospheric chemistry, the global water cycle, geo-hazards, and coral reefs as part of a future coastal initiative.

Bilateral agreements provide another strategy for achieving partnerships in observations and monitoring. Additionally, activities such as the U.S.-led Earth Observations Summit, the Subsidiary Body for Scientific and Technical Advice (SBSTA) meetings, and UNFCCC Conferences of the Parties provide opportunities to build international consensus—both scientific and political—for the implementation of a more integrated global climate observing system.

Objective 5.2: Provide support for key observations in developing countries

Developing countries provide key opportunities and challenges for observing systems. While many developing countries have the potential to make routine weather observations, and do so on a regular basis, many do not have the capability to collect and disseminate reliable observations of other variables that are critical for climate characterization and understanding. Further, many developing countries do not have adequate human resources to take full advantage of climate projections that would yield many benefits to their citizens.

It has been established that many developing countries lack either the capital or human resources to support high-quality observations or to sustain data and information systems. Countries often lack adequate capital for investment in equipment and supplies, trained technical staff, or maintenance capability.

The U.S. research community can point to numerous examples where it has contributed to measurements of key variables in developing countries. Many of these have provided valuable long-term data. The networks to measure atmospheric constituents through flask sampling and through vertical soundings have contributed a global database of important information on greenhouse gases. The oceanographic community has successfully engaged many coastal nations to participate in one or more of its observing systems (e.g., sea level, drifting floats and buoys, volunteer ships, etc.). International programs addressing terrestrial processes have demonstrated similar successes in observing ecosystems, obtaining hydrologic information, and initiating cryospheric measurement.

CCSP has specifically noted the key role that the United States can play in improving observational networks. In the President's June 2001 Rose Garden speech, he stated that "We'll also provide resources to build climate observation systems in developing countries and encourage other developed nations to match our American commitment."

The United States can contribute further by:

- Evaluating existing networks' capability to meet established climate requirements
- Improving existing networks through direct contributions to international programs [e.g., the World Meteorological Organization's (WMO) Voluntary Cooperation Programme]
- Forming partnerships with other developed countries to make directed investments to meet developing country inadequacies
- Providing direct assistance through U.S. programs of aid to specific developing country activities, such as the U.S. Agency for International Development (USAID)
- Continuing and expanding the collaborative international scientific programs that address critical climate variables.

Objective 5.3: International coordination through membership in key international groups

It is essential for the United States to maintain a leadership role in those international programs, both research and operational, that support climate observations of importance to U.S. programs. The principal international research programs (e.g., the World Climate Research Programme, the International Geosphere-Biosphere Programme, and the International Human Dimensions Programme) invite members from the U.S. scientific community and often from federal agencies to serve on relevant steering committees and working groups. These committees and working groups provide a forum for planning future research campaigns and for developing observational components that often lead to continuing measurement strategies. Individuals participating in these groups provide key links between U.S. and international research programs.

With regard to observations, U.S. scientists serve on the steering committees and working groups of the global observing systems and provide continuing advice to them. The principal programs for atmosphere, ocean, and terrestrial observations of climate include GCOS, GOOS, and GTOS, as well as their working groups.

U.S. scientists also serve on more operationally oriented international committees that support ongoing observational activities. Examples include the Commissions of the WMO (e.g., Basic Systems, Climatology, Hydrology, etc.) and the Joint Commission for Oceanography and Marine Meteorology sponsored by WMO and the Intergovernmental Oceanographic Commission. Individuals named to such groups serve as national representatives. These groups establish observing requirements, develop protocols for data and information exchange, and obtain international commitments.

CCSP encourages U.S. scientists to continue their important roles in support of these diverse international programs.

Goal 6: Manage the observing system with an effective interagency structure.

The development of a national observing and monitoring system will require a coordinated management plan, which involves all federal agencies that conduct research and operational observations of the climate system. The management approach described in this goal follows the general guidelines outlined in Chapter 16. However, based upon the "best practices" learned over the history of USGCRP, a more detailed management structure is described for the observation system within this goal. Experience has shown that scientific oversight is key for the maintenance of climate-quality data from observing systems; consequently, the management plan will engage the science and user communities in key oversight and evaluation capacities. Finally, the observing system will be global and carried out with the nations of the world; therefore, cooperation at the international level for both operational and scientific oversight will need further development (see Goal 5).

At present, some of these management elements are in place, but a well-coordinated national management plan for observing the climate system is not, and will be addressed in the coming decade. At the federal level, coordination at the program level will be strengthened to address implementation, and oversight by agency principals will be established. Scientific oversight will occur through a layered pyramid of working groups starting at the most basic level of instrument teams and building up to an observing system science advisory council. This structure has been demonstrated to be an effective strategy over the lifetime of USGCRP and this goal expands the "best practices" learned to the observing system as a whole.

Objective 6.1: Provide coordinated management groups for the observing system elements

The management of the observing system elements will vary depending on size and complexity. Space systems, both operational and research, require focused project management groups that are dedicated to monitoring health and safety, providing command and control, receipt and quality control of downlinked data, fault recovery, and ground tracking, if necessary.

In situ systems can vary from control and maintenance of a single convenient site on land to maintenance of a large international network at sea. While the former can rely on a simple management program, the latter requires a much larger national management group and international coordination. CCSP will coordinate management groups of similar measurement techniques and logistics; coordinate with international management where applicable; work with international implementation coordination groups, such as the Joint Commission on Oceanography and Marine Meterology; and finally provide overall management and guidance for the national system as a whole through an interagency working group. The selection and oversight of management groups will depend on whether they are research or operational, and federal, commercial, or university.

Objective 6.2: Provide Climate Data Science Teams for climate data stewardship

The foundation of the management strategy is to obtain key CDRs through the use of CDSTs. Definition of the CDSTs is based on the last 2 decades of experience and lessons gained from previous Earth observation systems focused on climate measurements. A clear message from this experience is the need for CDSTs. These teams are composed of a group of scientists and engineers whose purpose is to convert raw instrument data into CDRs, including calibration, algorithm development, validation, error analysis, quality control, and data product design. If the data volume is small, the CDST may also produce and distribute the data products. If the data volume is large, the CDST may interface to a separate data center for production, archiving, and distribution.

Examples of effective CDSTs include the production of climate versions of the surface air temperature records; most NASA EOS satellite data products, as well as those of precursor activities such as the Total Ozone Mapping Spectrometer, Stratospheric Aerosol and Gas Experiment, and Active Cavity Radiometer Irradiance Monitor; the international Argo ocean profiling float program; the NOAA-led Baseline Surface Radiation Network; and DOE's ARM Program. The reason that CDSTs are required for most, if not all, climate data records is the extreme accuracy needed for rigorous climate records (see Objective 3.1). Because the methods of measurement vary so greatly, effective CDSTs focus on just a few of the climate data records, and some only on a single CDR. A minimal list of variables needed as CDRs is given in Appendix 12.1.

Most CDSTs are chosen by scientific peer review. They consist of a principal investigator and a set of co-investigators. The co-investigators lead key instrument, algorithm, sampling, validation, and data management functions. CDSTs include members of the climate modeling or climate analysis community (i.e., data users). This is key to keeping the CDST focused on the most effective approach to meeting users' needs. Most CDSTs are currently funded by a single U.S. agency. CDSTs have their work and products peer-reviewed. CDSTs are often used in national and international assessments of the state of climate science and climate impacts. They document the

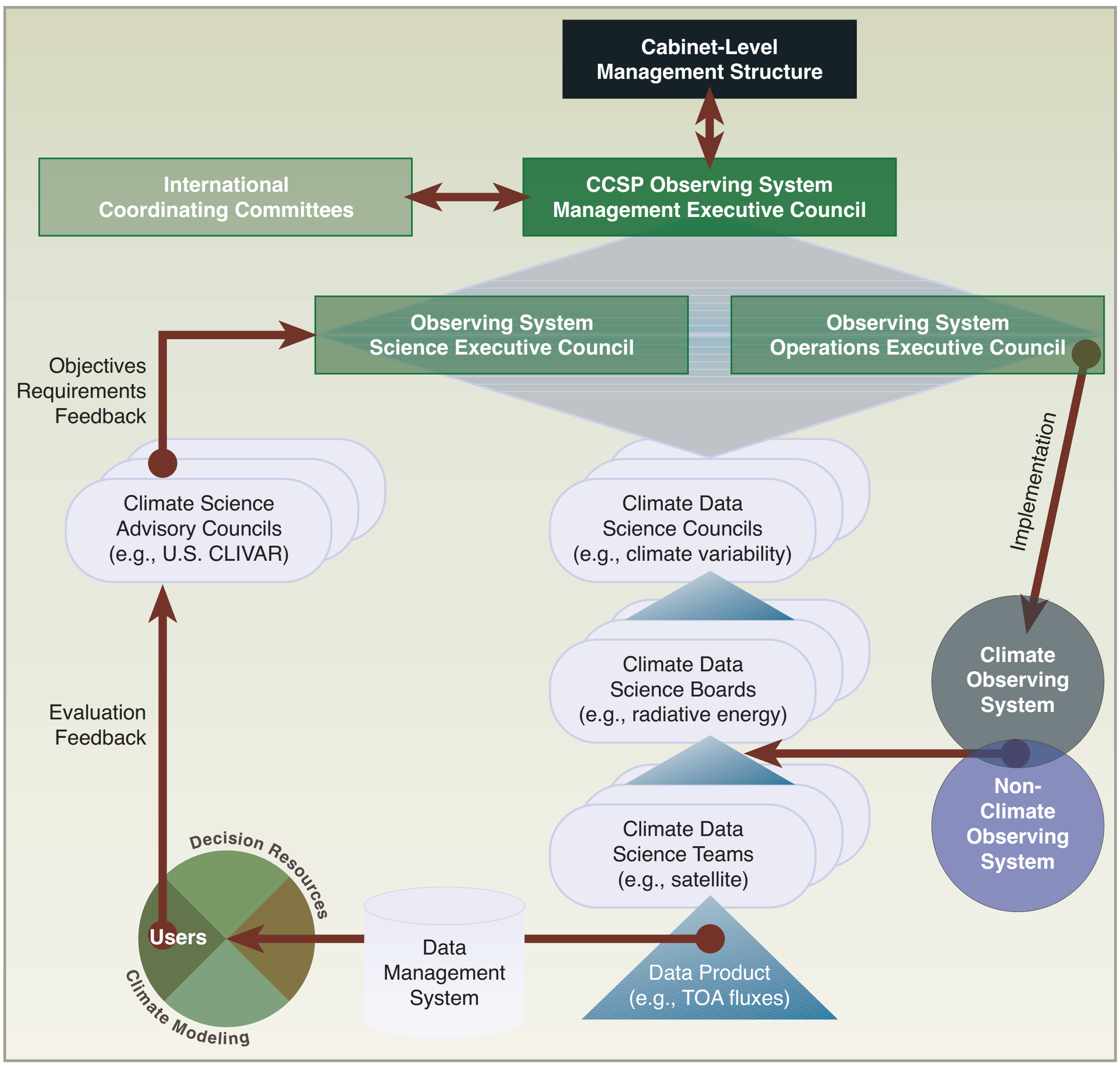

Figure 12-6: Schematic of the overall management structure for the observing system.

climate data products and their quality through web documents, conference papers, and journal papers.

Objective 6.3: Develop science and management advisory boards and councils to prioritize across climate system components and to guide system evolution

Observing system science direction will be provided by boards and councils. It is too long a step between a single CDST focusing on one or two climate variables and CCSP. A logical structure will be needed between these two extremes. The structure chosen must be able to handle the following set of changes and prioritizations:

- Evolving scientific understanding and changes in accuracy requirements
- Changing financial/human resources and delivery schedules
- Evolving technology for developing and implementing improvements
- Changing instrument, surface site, and spacecraft operations
- Changing data management interfaces and technology (e.g., production, distribution, and archival)
- User-driven changes in data product format requirements.

Addressing these trade-offs between resources, requirements, and climate variables will require a hierarchical science management committee structure. While there are many ways to provide such a structure, climate data and climate modelers will be best served by a structure that gives highest priority to tight integration of major climate system components (see Figure 12-6). Portions of such a system have evolved over the last decade, primarily at the international level as discussed under Goal 5. It is most fully evolved and effective for ocean observations, while the process for terrestrial observations is at a much earlier stage of development. More of this structure will be developed by CCSP for the United States.

The CCSP cabinet-level management structure is at the top level, responsible for resource commitments to the climate observing system.

The second level consists of a sub-group of CCSP—the Observing System Management Executive Council (OSMEC), composed of agency executives capable of committing agency funding. This group will provide a formal interface with international coordination groups, such as CEOS and IGOS-P.

Two groups comprise the third level. The first is an interagency program management group responsible for providing resources to implement the observations and to support science investigations—the Observing System Operations Executive Council (OSOEC). The second is the highest level science advisory group—the U.S. Observing System Science Executive Council (OSSEC). This science council makes recommendations to both OSMEC and OSOEC by prioritizing across the entire climate observing system. In addition, OSSEC will develop the objectives and requirements for the observing system, based on input from the Climate Science Advisory Councils of the research elements and decision support groups, and will evaluate the ability of the observing system to meet these objectives. These Climate Science Advisory Councils will also provide OSSEC with evaluation reports on the performance of the system in meeting the needs of its users.

At the fourth level, Climate Data Science Councils are responsible for climate observations to support each of the seven major CCSP research elements: Atmospheric Composition, Climate Variability and Change, Water Cycle, Land-Use/Land-Cover Change, Carbon Cycle, Ecosystems, and Human Contributions and Responses, as well as Decision Support activities. The Climate Data Science Councils could be a sub-group of the Climate Science Advisory Councils shown in Figure 12-6. Some of the Climate Science Advisory Councils already exist, such as the U.S. Climate Variability and Predictability (CLIVAR) team for the Climate Variability and Change theme. The Climate Data Science Councils address the complete range of climate variables within their theme.

A minimum set of climate variables is given in Appendix 12.1. Some variables will be relevant to several of the Climate Data Science Councils. Such overlaps are inevitable in any management structure given the tight coupling of processes in the climate system. It is the responsibility of OSSEC to assign primary responsibility for each variable to one of the Climate Data Science Councils. The Climate Data Science Councils are responsible for setting CDR requirements for absolute accuracy, stability, and space/time sampling.

At the fifth level, Climate Data Science Boards will address data parameters grouped into the most natural subsets for climate processes and/or for the type of instrumentation. For example, one of the Climate Variability and Change science boards would cover radiative energy from the top of atmosphere to the surface of the Earth. Some of these groups have already been formed by individual agencies (e.g., sea surface topography, ocean winds, sea surface temperature, and ocean color within NASA). Within each Science Board there are *in situ*, satellite, and field experiment observations. The advantage of this approach is that the linkages of surface, satellite, and *in situ* data types for key climate parameters are actively considered in any observing system trade-offs and will be valuable to the implementation decisions of OSOEC. Each CDST will report to the relevant Climate Data Science Board.

The Climate Data Science Boards and Executive Councils will meet as required to assess progress in the data system, nominally once per year. These meetings are expected to be indepth workshops sufficient to deal with the complex trade-offs and linkages between the observing system components. Every 5 years, a major assessment of the entire climate observing system would be produced, reviewed by the National Research Council, and coordinated with international assessments (e.g., the International Conference on Ocean Observing Systems for Climate, GCOS Adequacy Reports, IPCC assessments).

These boards and councils must include members of the climate data user community (e.g., climate modelers, climate analysts), as well as CDST representatives and data management representatives. In addition, members of the community who participate in international science or operations groups will be *ex officio* members of their appropriate counterpart board or council. The most efficient organization will be to maximize the extent that the data management and climate modeling management structures parallel that of climate observing and monitoring.

Objective 6.4: Provide a management structure that allows clear interagency responsibility, prioritization, peer review, and evolution of the observing system

Observations and monitoring of the climate system are carried out by a number of federal agencies. Success will require a series of steps to be initiated jointly by OSMEC, OSOEC, and OSSEC. These steps include:

- Assign agency responsibility for measurement contributions to each variable and measurement type. These contributions would typically be defined in terms of measurement system (satellite, *in situ*, field experiment) and sampling (e.g., satellite orbits, number/location of ground sites). OSSEC will be necessary in this step in order to ensure that the climate monitoring principles (see Appendix 12.4) are adhered to in assigning these responsibilities and evaluating the ability of the observations to meet the science objectives and requirements. If more than one agency is involved in measuring a single parameter, OSSEC must clearly define the responsibilities of each. Given the need for independent observations, it is recommended that the United States and the international community each provide at least one measurement of each variable. This would ensure the absolute minimum of two observations for each key climate variable.
- Assess the state of the climate observing system, including current agency plans. This assessment must include climate observing system requirements for each component as well as current and planned capabilities.
- Once shortcomings are identified, the Executive Councils (Science, Operations, and Management) and international groups must coordinate a plan for eliminating these shortcomings over time.
- Select the CDSTs for each climate variable, preferably through peer review. Typically, for any given variable, there will be separate CDSTs for surface and satellite observations. This is dictated by the large differences in instrumentation, calibration, operations, and sampling for these systems.

CHAPTER 12 AUTHORS

Lead Authors
Chester Koblinsky, NASA and CCSPO
Thomas Spence, NSF
Waleed Abdalati, NASA
Michael Dettinger, USGS
Howard Diamond, NOAA
Michael Johnson, NOAA
Thomas Karl, NOAA
James Mcguire, NASA
Lawrence Pettinger, USGS
Sushel Unninayer, NASA
Bruce Wielicki, NASA

Contributors
Jeff Amthor, DOE
James Andrews, ONR
James Butler, NOAA
Margarita Conkright, NOAA and CCSPO
Wanda Ferrell, DOE
Gerald Fraser, NIST
David Goodrich, NOAA
Carol Johnson, NIST
Jack Kaye, NASA
William Kirby, USGS
Laura Miner-Nordstrom, USEPA
Steve Piotrowicz, NOAA
Cynthia Rosenwieg, NASA
David Shultz, USGS
Brent Smith, NOAA
Sidney Thurston, NOAA

APPENDIX 12.1

EARTH CLIMATE SYSTEM OBSERVATIONS

This table provides a summary of "State" and "Forcing/Feedback" variables for the major components of the Earth system for which observations are required. In parentheses, "I" and "S" denote measurements made by *in situ* and space-based instruments, respectively. See Annex C for source information.

STATE VARIABLES	EXTERNAL FORCING OR FEEDBACK VARIABLES
(1) Atmosphere	
• wind (I/S) • upper air temperature (I/S) • surface air temperature (I/S) • sea-level pressure (I) • upper air water vapor (I/S) • surface air humidity/water vapor (I/S) • precipitation (I/S) • clouds (I/S) • liquid water content (I/S)	• sea surface temperature (I/S) • land surface soil moisture/temperature (I/S) • land surface structure and topography (I/S) • land surface vegetation (I/S) • CO_2 and other greenhouse gases, ozone and chemistry, aerosols (I/S) • evaporation and evapotranspiration (I/S) • snow/ice cover (I/S) • shortwave and longwave surface radiation budget (I/S) • solar irradiance and shortwave/longwave radiation budget (S)
(2) Ocean	
• upper ocean currents (I/S) • sea surface temperature (I/S) • sea-level/surface topography (I/S) • sea surface salinity (I/S) • sea ice (I/S) • wave characteristics (I/S) • mid- and deep-ocean currents (I) • subsurface thermal structure (I) • subsurface salinity structure (I) • ocean biomass/phytoplankton (I/S) • subsurface carbon (I), nutrients (I) • subsurface chemical tracers (I)	• ocean surface wind and wind stress (I/S) • incoming surface shortwave radiation (I/S) • downwelling longwave radiation (I/S) • surface air temperature/humidity (I/S) • precipitation (freshwater/salinity flux) (I/S) • evaporation (I/S) • freshwater flux from rivers and ice melt (I/S) • CO_2 flux across the air-sea interface (I) • geothermal heat flux—ocean bottom (I) • organic and inorganic effluents (into ocean) (I/S) • biomass and standing stock (I/S) • biodiversity (I) • human impacts—fishing (I) • coastal zones/margins (I/S)
(3) Terrestrial	
• topography/elevation (I/S) • land cover (I/S) • leaf area index (I) • soil moisture/wetness (I/S) • soil structure/type (I/S) • permafrost (I) • vegetation/biomass vigor (I/S) • water runoff (I/S) • surface ground temperature (I/S) • snow/ice cover (I/S) • subsurface temperature and moisture (I/S) • soil carbon, nitrogen, phosphorus, nutrients (I) • necromass (plant litter) (I) • subsurface biome/vigor (I) • land use (I/S) • groundwater and subterranean flow (I) • lakes and reservoirs (I/S) • rivers and river flow (I/S) • glaciers and ice sheets (I/S) • water turbidity, nitrogen, phosphorus, dissolved oxygen (I/S)	• incoming shortwave radiation (I/S) • net downwelling longwave radiation (I/S) • fraction of absorbed photosynthetically active radiation (I/S) • surface winds (I) • surface air temperature and humidity (I/S) • albedo (I/S) • evaporation and evapotranspiration (I/S) • precipitation (I/S) • land use and land-use practices (I/S) • deforestation (I/S) • human impacts—land degradation (I/S) • erosion, sediment transport (I/S) • fire occurrence (I/S) • volcanic effects (on surface) (I/S) • biodiversity (I/S) • chemical (fertilizer/pesticide and gas exchange) (I) • waste disposal and other contaminants (I) • earthquakes, tectonic motions (I/S) • nutrients and soil microbial activity (I) • coastal zones/margins (I/S)

APPENDIX 12.2

ILLUSTRATIVE RESEARCH MILESTONES FOR OBSERVATIONS AND MONITORING

This table provides examples of observing priorities highlighted in the research element chapters (Chapters 3-9) of this plan.

Atmospheric Composition

- Continue baseline observations of atmospheric composition over North America and globally.
- Improve description of the global distributions of aerosols and their properties.
- Develop and improve inventories of global emissions of methane, carbon monoxide, nitrous oxide, and nitrogen oxides (NO_x) from anthropogenic and natural sources.
- Monitor global distributions of tropospheric ozone and some of its precursors (e.g., NO_x).
- Continue monitoring trends in ultraviolet radiation.

Climate Variability and Change

- Improve effectiveness of observing systems, including deployment of new systems and re-deployment of existing systems, as well as the collection of targeted paleoclimatic data.
- Improve estimates of global air-sea-land fluxes of heat, moisture, and momentum.
- Regularly update and extend global climate reanalyses.
- Conduct process studies for needed observations of critical ocean mixing processes.
- Develop a paleoclimatic database to evaluate climate models.

Water Cycle

- Develop an integrated global observing strategy for water cycle variables.
- Characterize water vapor in the climate-critical area of the tropical tropopause.
- Monitor drought based on improved measurements of precipitation, soil moisture, and runoff.
- Test parameterizations for clouds and precipitation processes.
- Initialize and test boundary layers and other components in models.

Land-Use/Land-Cover Change

- Continue to acquire global calibrated coarse-, moderate-, and high-resolution remotely sensed data.
- Provide global maps of areas of rapid land-use and land-cover change, and location and extent of fires.
- Quantify rates of regional, national, and global land-use and land-cover change.
- Develop global high-resolution satellite land-cover databases.
- Provide operational global monitoring of land use and land-cover conditions.

Carbon Cycle

- Provide U.S. contributions to an international carbon observing system, including measurements of carbon storage, fluxes, and complementary environmental data.
- Assessment of the quality of measurements that support global carbon cycle science.
- Measure atmospheric carbon dioxide and methane concentrations and related tracers in under-sampled locations.
- Observe global air-sea fluxes of carbon dioxide, lateral ocean carbon transport, and delivery of carbon from the land to the ocean.
- Develop database of agricultural management effects on carbon emissions and sequestration in the United States.

Ecosystems

- Define requirements for ecosystem observations to quantify feedbacks to climate and atmospheric composition, to enhance existing observation systems, and to guide development of new capabilities.
- Quantify biomass, species composition, and community structure of terrestrial and aquatic ecosystems in relation to disturbance patterns.
- Maintain and enhance satellite terrestrial, atmospheric, and oceanic observing systems and networks, to monitor trends in ecosystem variables to parameterize models and verify model projections.
- Continue and enhance long-term observations to track changes in seasonal cycles of productivity, species distributions and abundance, and ecosystem structure.
- Provide data quantifying aboveground and belowground effects of elevated carbon dioxide concentration in combination with elevated ozone concentration on the structure and functioning of agricultural, forest, and aquatic ecosystems.

Human Contributions and Responses to Environmental Change

- Gridded world population database, including time series as far as possible into the past.
- Human footprint data set that depicts the geographic extent of human impacts on the environment.
- Produce elevation maps depicting areas vulnerable to sea-level rise and planning maps depicting how state and local governments plan to respond to sea-level rise.

APPENDIX 12.3

CLIMATE CHANGE RESEARCH INITIATIVE (CCRI) ACTIVITIES IN OBSERVATIONS AND MONITORING

CCRI Milestones

Ocean Observations

CCRI funds will be used to work toward the establishment of an ocean observing system that can accurately document climate-scale changes in ocean heat content, carbon uptake, and sea-level changes. Global tropical measurements will be augmented to improve seasonal forecasts. Ocean reference stations will be added to improve routine analyses of ocean-atmosphere fluxes at these stations to improve energy balance studies and coupled modeling parameterizations. In addition, key locations will be instrumented to improve understanding of abrupt climate change detection. The requirements for ocean observations for climate have been well documented, the relevant technology is available, and the international community is mobilized through GCOS and GOOS to implement key elements of the system.

Atmosphere Observations

CCRI funds will be used to work with other developed countries to reestablish the benchmark upper air network, emphasizing data-sparse regions; to upgrade the GCOS surface network for baseline variables; to deploy mobile Atmospheric Radiation Measurement program facilities; to begin planning for an early copy of an NPOESS aerosol instrument; and to place new Global Atmospheric Watch stations in priority sites to measure pollutant emissions, aerosols, and ozone, in specific regions.

Aerosol Observations

Aerosols and tropospheric ozone play unique, but poorly quantified, roles in the atmospheric radiation budget. CCRI investments will be used to begin implementation of plans developed by the interagency National Aerosol-Climate Interactions Program to define and evaluate the role of aerosols that absorb solar radiation, such as black carbon and mineral dust. Proposed activities include field campaigns, *in situ* monitoring stations to measure black carbon and aerosol precursors, global climatologies of tropospheric aerosols, and satellite algorithm development.

Carbon Cycle Observations

Research objectives for carbon cycle science include improved observations to address some of the field's greatest areas of uncertainty. CCRI funds will be targeted for the integrated North American Carbon Program (NACP), a priority of the *U.S. Carbon Cycle Science Plan*. NACP calls for implementing a North American Carbon Cycle Observing System consisting of a network of small aircraft stations and tall towers to obtain profiles of carbon gases for determining sources and sinks of carbon dioxide in the United States, expansion of the AmeriFlux sites, the development of automated carbon dioxide and methane sensors, improvements in ground-based measurements, and inventories of forest and agricultural lands. In addition, funds are provided for improved estimates of carbon dioxide over and into the ocean derived from ship-based instruments.

In addition, CCRI will select and award development assistance projects for climate monitoring in developing nations.

APPENDIX 12.4

GCOS CLIMATE MONITORING PRINCIPLES[4]

Effective monitoring systems for climate should adhere to the following principles:

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. The details and history of local conditions, instruments, operating procedures, data processing algorithms, and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional, and global observing priorities.
6. Operation of historically uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully planned manner should be promoted.
10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.

Furthermore, satellite systems for monitoring climate need to:

a. *Take steps to make radiance calibration, calibration monitoring, and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system.*
b. *Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved.*

Thus, satellite systems for climate monitoring should adhere to the following specific principles:

11. Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained.
12. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.
13. Continuity of satellite measurements (i.e., elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.
14. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured.
15. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.
16. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.
17. Data systems needed to facilitate user access to climate products, metadata, and raw data, including key data for delayed-mode analysis, should be established and maintained.
18. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.
19. Complementary *in situ* baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.
20. Random errors and time-dependent biases in satellite observations and derived products should be identified.

[4]The ten basic principles were adopted (in paraphrased form) by the Conference of the Parties (COP) to the U.N. Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November 1999.