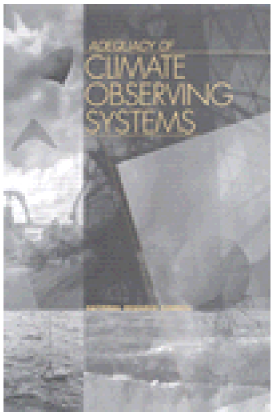

Adequacy of Climate Observing Systems

Panel on Climate Observing Systems Status, Climate Research Committee, National Research Council

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Adequacy of Climate Observing Systems

Panel on Climate Observing Systems Status
Climate Research Committee
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources

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Foreword

There is nothing more precious to scientists than the measurements and observations required to confirm or contradict theories and hypotheses. No matter how fundamental the theory or hypothesis, observations are the building blocks of science.

In the earth sciences, and in particular the climate sciences, there is a peculiar relation between the scientist and the data. Unlike many other sciences, where strict laboratory controls, or at least day-to-day scientific oversight of measurements is the rule, in order to detect changes in the Earth's climate and attribute these to specific causes, multivariate observations are required over long periods of time, on a global basis, and in a synoptic sense. Climate scientists focusing on this task must therefore rely on observations and data collected by a whole suite of observing systems operated by various countries. The instrumentation, observing practices, processing algorithms, and data archive methods used by these countries profoundly affect the progress of understanding climate change.

Such a relationship to observations and data is nothing new to meteorologists. To help overcome this divorce between the scientist and their data, decades ago meteorologists developed the World Weather Watch program coordinated through the World Meteorological Organization. Its success has been a model of human cooperation and ingenuity. It has enabled meteorologists in forecast offices anywhere in the world to take advantage of our increased understanding of the atmospheric sciences and provide improved weather forecasts.

Is an analogous system needed for the climate sciences? Are we making the measurements, collecting the data, and making it available in a way that both today's scientist, as well as tomorrow's, will be able to effectively increase our understanding of natural and human-induced climate change? The Panel on Climate Observing Systems Status would answer the latter question with an emphatic NO. Given the potential impact of anthropogenic climate change on our society and in a worst-case scenario a catastrophic change in climate, there is an urgent need for improving the record of performance. This report is an attempt to help illuminate the importance of multi-decadal climate monitoring.

THOMAS R. KARL, *CHAIR*

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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Executive Summary

In December 1997 in Kyoto, Japan, the community of nations reached a historic agreement to collectively curb the growth of carbon dioxide and other radiatively active gases in the atmosphere. The intense 1997–1998 El Niño, although not necessarily related to the carbon dioxide increase, made clear the importance of climate variations. The event caused anomalous weather, some of it beneficial (fewer hurricanes in the Atlantic), but much of it adverse (record rainfall in the western and southern portions of the United States and drought in Indonesia). Agriculture, ecosystems, water supply systems, and public health are potentially vulnerable to natural variability and changes in climate. The leaders of the developed and developing nations recognize that climate changes are likely to have significant impacts on their economies, foreign policies, and quality of life in the coming decades.

The 1997 Conference on the World Climate Research Programme to the Third Conference of the Parties of the United Nations Framework Convention on Climate Change concluded that the global capacity to observe the Earth's climate system is inadequate and is deteriorating worldwide: *"Without action to reverse this decline and develop the Global Climate Observation System, the ability to characterize climate change and variations over the next 25 years will be even less than during the past quarter century"* (See Appendix A). As a result, the chair of the subcommittee of the U.S. Global Change Research Program (USGCRP) requested a National Research Council study to assess the current status of the climate observing capabilities of the United States. This report focuses on existing observing systems for detection and attribution of climate change, with special emphasis on those systems with long time series.

As will be shown in this report, these systems require immediate action to reverse their decay and to redesign them.

Climate impacts most economic sectors, including energy, food and fiber, transportation, human health, biological resources, and living conditions. These activities are influenced by precipitation and water availability, temperature, storms, solar radiation, and sea level, and how they vary over time and with geography. Variables most useful for climate change detection and attribution are: three-dimensional temperature and water vapor; surface wind, sea level pressure, precipitation; sea ice and ice sheet properties; streamflow, groundwater and land water reservoirs; vegetation cover; and ocean upper-level temperature and salinity, deep ocean temperature and salinity profiles and the height of sea level.

Most observing systems that monitor climate were established to provide data for defined purposes, such as predicting daily weather; advising farmers; warning of hurricanes, tornadoes and floods; managing water resources; aiding ocean and air transportation; and understanding the role of the ocean in climate change. Many federal and state agencies, including the Departments of Agriculture, Commerce, Defense, and Interior, and NASA, collect these data. In some departments, several agencies operate observing systems. For example, in Defense, the Air Force, Navy, and Corps of Engineers operate networks that observe some of these variables.

The purpose of these observations continues to evolve with changes in mission, with the development of new technologies, and more recently with restrictions on budgets. The priorities to maintain the observation networks vary widely from agency to agency. In general, management of the programs has not recognized the importance of the observations for detection and attribution of climate change. **The departments and agencies should strengthen and revitalize the partnerships that generated long-term records of many of these variables.**

Climate researchers have used existing, operational networks because they have been the best, and sometimes only, source of data available. They have succeeded in establishing basic trends of several aspects of climate on regional and global scales. Deficiencies in the accuracy, quality, and continuity of the records, however, still place serious limitations on the confidence that can be placed in the research results. **Federal agencies should undertake a joint effort to improve the observations from these networks.**

The panel concludes that the ten climate monitoring principles proposed by Karl et al., 1995, should be applied to climate monitoring systems:

1. **Management of Network Change:** Assess how and the extent to which a proposed change could influence the existing and future climatology

obtainable from the system, particularly with respect to climate variability and change. Changes in observing times will adversely affect time series. Without adequate transfer functions, spatial changes and spatially dependent changes will adversely affect the mapping of climatic elements.

2. **Parallel Testing:** Operate the old system simultaneously with the replacement system over a sufficiently long time period to observe the behavior of the two systems over the full range of variation of the climate variable observed. This testing should allow the derivation of a transfer function to convert between climatic data taken before and after the change. When the observing system is of sufficient scope and importance, the results of parallel testing should be documented in peer-reviewed literature.
3. **Metadata:** Fully document each observing system and its operating procedures. This is particularly important immediately prior to and following any contemplated change. Relevant information includes: instruments, instrument sampling time, calibration, validation, station location, exposure, local environmental conditions, and other platform specifics that could influence the data history. The recording should be a mandatory part of the observing routine and should be archived with the original data. Algorithms used to process observations need proper documentation. Documentation of changes and improvements in the algorithms should be carried along with the data throughout the data archiving process.
4. **Data Quality and Continuity:** Assess data quality and homogeneity as a part of routine operating procedures. This assessment should focus on the requirements for measuring climate variability and change, including routine evaluation of the long-term, high-resolution data capable of revealing and documenting important extreme weather events.
5. **Integrated Environmental Assessment:** Anticipate the use of data in the development of environmental assessments, particularly those pertaining to climate variability and change, as a part of a climate observing system's strategic plan. National climate assessments and international assessments, (e.g., international ozone or IPCC) are critical to evaluating and maintaining overall consistency of climate data sets. A system's participation in an integrated environmental monitoring program can also be quite beneficial for maintaining climate relevancy. Time series of data achieve value only with regular scientific analysis.
6. **Historical Significance:** Maintain operation of observing systems that have provided homogeneous data sets over a period of many decades to a century or more. A list of protected sites within each major observing system should be developed, based on their prioritized contribution to documenting the long-term climate record.
7. **Complementary Data:** Give the highest priority in the design and implementation of new sites or instrumentation within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and

key measurements with inadequate temporal resolution. Data sets archived in non-electronic format should be converted for efficient electronic access.

8. **Climate Requirements:** Give network designers, operators, and instrument engineers climate monitoring requirements at the outset of network design. Instruments must have adequate accuracy with biases sufficiently small to resolve climate variations and changes of primary interest. Modeling and theoretical studies must identify spatial and temporal resolution requirements.
9. **Continuity of Purpose:** Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.
10. **Data and Metadata Access:** Develop data management systems that facilitate access, use, and interpretation of data and data products by users. Freedom of access, low cost mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.), and quality control should be an integral part of data management. International cooperation is critical for successful data management.

The panel's evaluation of existing climate records, using these ten principles, shows that only about half of the principles are being followed for some of the variables most useful for climate change detection and attribution. For other records, only one or two principles are being followed adequately. The application of all but one of the principles of climate monitoring needs improvement.

If federal agencies are to serve society's needs for well-informed climate decisions, they should strive to preserve the value of the past climate record and to build improved and more valuable climate records in the future. Although this report focuses on existing observational systems, especially those with long data records, it is important to stress that this represents only a part of the needs for climate data. **Programs to develop new records also should be undertaken, and should take advantage of such new technology as geostationary and polar orbiting satellites.**

A word of caution, however: for many years, satellite remote sensing has been suggested as the answer to climate monitoring. Indeed, the growing emphasis on operational mesoscale weather observing and forecasting initiatives inevitably will lead to a growing reliance on remote sensing—both surface- and space-based. If, in the process, in situ networks such as the radiosonde are reduced in size or importance, there could be a large negative impact on the ability to assess climate and climate change. The panel recognizes that many of the atmospheric observations in ocean areas can be provided only by global systems such as satellites. At the moment, however, there is only sketchy information on the suitability of remotely sensed data as a source for climate change detection and attribution. Some studies have shown a positive impact of these data. Others have clearly indicated substantial problems, two of which are calibration and poorly documented changes in the instrument performance from one satellite to the next.

FINDING: There has been a lack of progress by the federal agencies responsible for climate observing systems, individually and collectively, toward developing and maintaining a credible integrated climate observing system, consequently limiting the ability to document adequately climate change.

RECOMMENDATION: These agencies should work through the USGCRP process and at higher government levels to:

- **stabilize the existing observational capability;**
- **identify critical variables that are inadequately measured;**
- **build climate observing requirements into the operational programs as a high priority;**
- **revamp existing climate programs and some climate-critical parts of operational observing programs through the implementation of the ten principles of climate monitoring; and**
- **establish a funded activity for the development, implementation, and operation of climate-specific observational programs.**

In the near term, the USGCRP agencies can ameliorate this situation by taking the following actions:

1. All agencies operating climate-relevant observation systems should adopt and implement the set of climate monitoring principles outlined above.
2. System performance measures should be developed and monitored on a regular basis. It would be unwise to wait for a major environmental assessment or data archeology effort to discover that problems that occurred 10 or 20 years earlier had already inflicted considerable damage on the climate record. An institutional infrastructure should be developed to assess the quality of data sets and correct problems as they occur.
3. Accelerate access by the research community to climate-related observation data bases, primarily in non-electronic formats, that reside deep in agency archives.
4. The free, open, and timely exchange of data should be a fundamental U.S. governmental policy and, to the fullest extent possible, should be enforced throughout every federal agency that holds climate-relevant data. Adherence to this principle should be promoted more effectively by the U.S. government in its international agreements, with particular attention given to implementation.
5. Vastly improved documentation of all changes in equipment, opera

tions, and site factors in operational observing systems is required to build confidence in the time series of decadal-to-centennial climate change.

6. Establish and maintain strong, robust links between operational systems managers and the climate data users.
7. Because U.S. economic and social interests depend on knowing the climate globally, U.S. agencies should pursue international cooperation in climate observation and monitoring through international mechanisms. USAID funds may be one vehicle to ensure critical observations in developing countries.

1

Questions and Answers

This report uses a question and answer format to assist decision makers and their constituencies in understanding the complex issues related to the adequacy of climate observing systems. This discussion begins by providing a general awareness of climate variability, proceeds to review how climate data are obtained, and concludes with recommendations that will ensure adequate documentation over the next decades.

1. Why do we need to document climate variations? What are some of the consequences if we don't?

The basic science and the relevant technology available to scientists have enabled them to understand in broad outline the functioning of the global climate system. Scientists are beginning to understand what causes future climate change; they are beginning to detect and understand decadal climate variability, and have built working, albeit incomplete, models of the Earth's climate system. They have modeled and projected the climatic effects of the anthropogenic addition of carbon dioxide and aerosols to the atmosphere. The longer-range projections of climate change, however, are more uncertain than making an El Niño forecast, for example. Much more remains to be understood about the long-term drivers of climate change. This topic is discussed extensively in *Decade-to-Century-Scale Climate Variability and Change: A Science Strategy* (NRC, 1998a).

The 1997–1998 El Niño, one of the most publicized examples of recent natural climate variability, markedly modified rainfall patterns, creating intense droughts in some regions and devastating floods in others. Scientists have made substantial progress in understanding and predicting El Niño events, and society has used such predictions to reduce societal and economic costs of El Niño.

(WMO Secretary General Obasi recently summarized the status of the predictions and impacts of the 1997–1998 El Niño event at the First Intergovernmental Meeting of Experts on El Niño at Guayaquil, Ecuador [WMO, 1998].)

Other types of natural climate variability can also produce shifts in storminess and rainfall over large continental regions. For example, warmer patterns can increase evaporation and accelerate water circulation through the atmosphere, modifying temporal and spatial rainfall patterns. Some models of increased greenhouse gases show that more rapid drying of continental interiors is also likely to occur, possibly increasing drought conditions during the summer months (IPCC, 1995). Agriculture, ecosystems, and water supply systems could all be vulnerable to such changes. Developed countries can adapt socioeconomic systems to the changing climatic conditions with the application of technology and investment of financial resources. Developing countries are much more vulnerable to these changes and their fragile infrastructures could be seriously affected.

Many decision makers and scientists now believe that climate changes already underway are likely to have significant effects on the U.S. economy, foreign policy, and quality of life in the coming decades. The recent IPCC Second Assessment Report of Climate Change (1995), concludes that prudent societal behavior mandates an awareness of current and pending climate changes and an assessment of the risks and benefits involved.

Quite apart from the effects of observable changes in our climate, several international treaties bear on the subject. The U.S. commitments to the United Nations Framework Convention on Climate Change (FCCC) and its protocols could lead to additional changes in the U.S. economy, patterns of living and employment, and domestic and foreign policies. Several countries, including the United States, developed and ratified the FCCC on the basis of scientific consensus on the likelihood of future climate change contained in the IPCC's First Assessment Report (IPCC, 1990). A major objective of the FCCC is the stabilization of atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system.

The FCCC not only provides for internationally coordinated emission restrictions, it also contains commitments to climate research and observations (see Appendix A). Moreover, at the Third Conference of the Parties in Kyoto in 1997, a resolution was adopted that "(u)rges the Parties to provide the necessary resources to reverse the decline in the existing observational networks and to support the regional and global observational systems being developed under the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS), through appropriate funding mechanisms." The Fourth Conference of the Parties, held in Buenos Aires in 1998, further stressed the need for observing systems. (See Appendix E)

In summary, decision makers in state and local governments and the private sector, as well as individual citizens, need assessments of probable future climate change based on data provided by the international climate observing system. The implications of longer-term climate change on society are so extensive that a scientifically sound approach is essential to assess the impacts of such change. Decision makers can then devise mitigation strategies and exploit the potential benefits. Early detection of accelerated climate change, and its attribution to natural or anthropogenic causes, could lead to more effective societal responses. It should also be noted that early, high-confidence detection of climate change could lead to the conclusion that the impacts would be less than previously estimated. Whether the impacts of climate change turn out to be large or small, negative or positive, accurate knowledge of climate variability is particularly important for policy decisions which may have multi-decadal implications. It is essential, in this situation, that the U.S. government has accurate information on which to base decisions.

This report will focus primarily on U.S. systems. Climate, however, is a global phenomenon, and to be properly understood, needs global observations. In the words of FCCC Decision 14/CP.4, the conference:

"Invites the agencies participating in the Climate Agenda, in consultation with the Global Climate Observing System Secretariat, to initiate an inter-governmental process for addressing the priorities for action to improve global observing systems for climate in relation to the needs of the Convention and, in consultation with the Convention secretariat and other relevant organizations, for identifying immediate, medium-term and long-term options for financial support. . ." (See Appendix E)

The United States plays a major role in international climate programs with leadership derived from its knowledge base, financial resources, and influence. However, it cannot do the job alone or base policy decisions on U.S. data alone. **Because U.S. economic and social interests depend on knowing the climate globally, U.S. agencies should pursue international cooperation in climate observation and monitoring through international mechanisms. USAID funds may be one vehicle to ensure critical observations in developing countries.**

2. What needs to be measured to describe the climate and to document climate variations and changes?

Examining the ways humans depend on or respond to climate helps identify the physical climate variables most important to sustaining life and human well-being. Food production and agricultural systems depend on local air temperature, precipitation, and the solar radiation during the growing season. Forests, which provide wood for construction as well as habitat for flora and fauna, depend on temperature and precipitation regimes. Water resources depend on precipitation and temperature, which controls evaporation and melting of ice and snow, and on the natural ecosystems that affect water storage and control its availability. Extremes of precipitation or changes in other portions of the hydrologic cycle can lead to droughts and floods. These are often accompanied by wildfire and severe soil erosion, endangering natural habitats, communities, and resources. Coastal regions are especially sensitive to changes in sea level. Long-term changes may involve only a slow rise in sea level, but water levels can rise rapidly during storm surges, inundating coastal communities and low-lying areas.

Human health depends directly on temperature and humidity, both of which contribute to heat stress and influence the transmission of infectious disease and the abundance of allergens. Ultraviolet radiation is necessary for the production of vitamin D, but it also contributes to skin cancer and influences air pollution levels. Ecosystems on land and in the ocean provide habitats for the diverse flora and fauna that supply food, medicine, recreation, and other resources—all of which depend on a wide array of climatic variables.

Six attributes of the Earth's complete climate system are especially important to society: (1) precipitation and water availability; (2) temperature; (3) storms; (4) solar radiation; (5) sea level; and (6) ecosystem structure and functioning. For each attribute, it is important to quantify the mean state or condition, variability over time scales from days to centuries, character and extent geographically, and the frequency and persistence of extreme values. The climate variables are discussed more completely in *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1998b) as well *Decade-to-Century-Scale Climate Variability and Change: A Science Strategy* (NRC, 1998a).

These climate variables also are relevant because of their importance to detection of climate change and the attribution of such change to a cause. Table 1 lists the combined minimum set of important climate variables. The variables addressed in this report appear in bold type in the table. The panel selected these variables based on two criteria: (1) their importance in understanding climate and (2) the existence of measurements using current operational and research systems.

Recent studies (NRC, 1995; 1998a; 1998b) have shown that the Earth's climate has exhibited patterns of natural variability on time scales ranging from years to tens of millennia. The variability over smaller subcontinental regions is even greater than that over entire continents or the Earth as a whole. Human-induced climate change will be superimposed on the natural variability or will modify it in ways that may not yet be fully understood (NRC, 1998a). Climate models have become increasingly important in understanding the nature of climate variability and the detection and attribution of climate change.

To be detectable the signal of climate change must be greater than the noise of natural variability. The accuracy of observations of a climate variable must exceed its natural variability on the time scale of interest (e.g., decades and

TABLE 1 Climate System Variables Relevant to Detection, Attribution, and Direct Societal Impacts

	Climate Change	Societal Impact
ATMOSPHERE		
(Surface)		
surface air temperatures	H	H
humidity (water vapor)	M	M
wind	L	H
radiative (skin) temperature		
sea level pressure	M	M
precipitation	M	H
snow cover extent (snowfall, water equivalent, and extent)	L	M
sea ice	L	H
incident solar radiation		
albedo		
downward longwave radiation		
streamflow	L	H
land water reservoirs (soil water, lakes, dams, rivers) and groundwater (well levels)	L	H
vegetative cover	L	H
fluxes of sensible and latent heat		
fluxes of atmospheric trace gases and particulate material		
(Vertical distribution throughout atmosphere)		
temperatures	H	L
humidity/water vapor	H	L
winds		
cloud properties		
aerosol properties		
chemical composition (CO_2, CH_4, O_3, ...)		
(Top of the Atmosphere)		
solar output (integrated and spectral)		
reflected solar radiation		
outgoing thermal radiation		
OCEANS		
sea level	M	H
sea surface temperature and salinity	H	M
upper ocean temperature and salinity	M	H
deep ocean temperature profile	M	M

Variables in bold are addressed in this report. Their importance to detection of climate change and their relevance on direct societal impacts, respectively, is denoted by: H = high, M = moderate, and L = low. Those variables measured with existing systems and judged most important in understanding climate are shown in bold, and are addressed in this report. Other variables, though generally of lower priority, were not explicitly ranked by the panel.

centuries). While it is difficult to reconstruct the past variability of climate, multi-century executions of global climate models, run with no changes in climate forcing, can increase confidence in estimates of climate variability. These climate models internally compute many of the variables appearing in bold type in Table 1. Therefore, long and consistent observations of these variables are needed to evaluate the model's true ability to simulate past climate. Most detection studies have used global patterns of the most accurately measured and longest observed climate variable—surface temperature—in their analyses. Consequently, observed and modeled trends in the patterns of surface temperature have frequently served as a surrogate for more general climate change. Recently, patterns of the vertical distribution of temperature changes throughout the atmosphere and changing frequencies of intense rainfall over land have been used successfully to detect and attribute human-induced climate change. Many of the bolded variables in Table 1 are critical for confirming and interpreting results of the climate models.

The ability of the research community to model the Earth's climate has improved over recent years, but approximations and parameterizations are still used extensively. Several levels of models have been used:

1. global atmosphere with non-responsive ocean;
2. global atmosphere, but with responsive ocean upper layer;
3. global atmosphere, responsive ocean, with continents;
4. coupled atmosphere-ocean models with shallow ocean only; and
5. coupled atmosphere-ocean models with deep ocean included.

Each level of model reproduces the climate record with greater fidelity, but each level places greater demands on the climate data. The more sophisticated data require more variables and longer records of those variables.

Once a climate change signal emerges above the natural background of climate variability, the cause for such change becomes of paramount interest. Possible causes could include external forcing from solar variability, volcanic activity, or one or a combination of human-induced forcings, such as increasing greenhouse gases, sulfate aerosols, ozone changes, and land use. As with the detection studies discussed above, climate models are essential for projecting patterns of climate change in response to alternative causes of climate forcings. By comparing the observed changes with the modeled responses to one or more simultaneous forcings, the cause of the observed change can be attributed if the signal exceeds the natural variability.

Although the models used to simulate climate have deficiencies themselves, a major limitation in the detection and attribution studies is the lack of sufficiently long, consistent records of observed climate variables. These records permit comparison with similar quantities generated from climate model experiments, thereby increasing confidence in the results. The future of definitive climate change detection and attribution lies in the use of multiple variables from observations and models.

It is important to note that this report deals only with the present sources of data for the detection and attribution of climate change. Assessing the state of systems for observing the principal *forcing factors* for climate change (such as atmospheric constituents, magnitude of the incoming solar radiation, cloud and particulate distribution, and volcanic activity) is outside the study task. However, to understand and document greenhouse gas-forced climate changes in the milieu of a naturally variable climate, it is also essential to develop and maintain adequate observing systems for many factors not included in bold face in Table 1.

3. How are climate data obtained?

There is today no comprehensive system designed to observe and document climate variability or climate changes. Those systems designed for climate purposes are either for unique parameters or operated for specific research purposes. Whereas international plans have been developed for assembling comprehensive global systems for monitoring climate, these plans all rely on the voluntary participation of countries around the world. At present, individual countries' climate observational capabilities, including those of the United States, rely almost entirely on a combination of their climate research activities and operational observing systems. Operational systems are fundamentally aimed at supplying the data necessary to serve some immediate societal purpose. These observing systems are operated or funded by many offices scattered throughout the federal and state governments, by individuals, and by private entities.

Precipitation is measured daily at 11,000 cooperative observing sites across the United States by volunteer observers using NOAA instruments. Minimum and maximum air temperatures and snow depth are measured at about half of these stations, and a few percent of the stations also record evaporation from evaporimeters during the growing season. This volunteer-operated network provides the best long-term temperature and precipitation climate data currently available, but it suffers from many problems ranging from inadequate instrumentation to data handling systems that are difficult to use. A comprehensive discussion of the network is contained in *Future of the National Weather Service Cooperative Observer Network* (NRC, 1998d). Crude precipitation estimates of uneven quality over the ocean result from a variety of satellite instruments, coastal radars, and island stations. At the present time no one system can provide a comprehensive, global view of precipitation; integration and blending of various data sets are required.

NOAA, DOD, and the FAA also operate a network of approximately 1,000 automated observing sites, mostly at airport locations, that measure hourly temperature, precipitation, humidity, winds, and other variables. With some exceptions, these sites have become only marginally useful for documenting climate variability and change over the last decades because of problems with changes in location, instrument technology, data handling systems, and operating procedures. These changes occurred without consideration of multi-decadal climate monitoring. In particular, the automated systems replaced manual observatories without sufficient overlap in operations to relate the data characteristics from the two methods of observation. However, with adequate sensitivity to their future operations, many of these sites have the potential to build a very useful climate record for the future.

Radiosondes (balloon-borne instruments) launched once or twice daily at over 700 sites globally measure the vertical distribution of temperature and humidity. The National Weather Service (NWS) operates nearly 100 sites, and about ten other sites receive partial NWS support. For the last 18 years, polar-orbiting satellites have augmented these temperature measurements with microwave sounding observations. Some problems remain in harmonizing these two sets of data. The research community is developing other means to observe the vertical distribution of water vapor in the atmosphere, but it will be a number of years before climatic observations will be available.

Sea surface temperatures are measured by ships of opportunity, several arrays of moored buoys, strategically deployed drifting buoys, coastal observing stations, and instrumentation on operational satellites. Upper ocean temperature is measured by expendable bathy-thermographs (XBTs) from ships of opportunity, the network of 70 moored buoys in the equatorial Pacific and the newly developed Profiling Autonomous Lagrangian Circulation Explorer (PALACE) floats, but the global oceans remain significantly undersampled. Deep ocean temperature and salinity are measured by ocean weather stations and during scientific cruises. Present remote-sensing technologies do not measure salinity adequately.

Streamflow, evapotranspiration, soil moisture, and groundwater are measured using a variety of networks. Streamflow is measured by gauging stations. The U.S. Geological Survey (USGS) manages the largest collection of these sites, which measure both natural changes in streamflow and changes due to anthropogenic withdrawals, diversions, and land use changes. Evapotranspiration is not directly measured systematically, but evaporation from water surfaces is measured directly for a few hundred sites in the United States during the growing season. Long-term measurements of evapotranspiration can be deduced only from modeling efforts or theoretical mass balance calculations. No national networks of soil moisture exist, but there are several statewide networks of soil moisture measurements, some that span two decades. Groundwater is measured at observation wells where water is not withdrawn. Snow water equivalent is measured by NOAA and the Natural Resource Conservation Service's manual snow course survey, which is being replaced by an automated network. The latter set of measurements may not be compatible with the manual snow course data. USGS collects long-term measurements of lake levels, but many changes in instrument locations have occurred over time, making it difficult to use the data.

An extensive network of tide gauges operated by NOAA to promote safe navigation measures sea level heights, but there is large spatial inhomogeneity, and many records are of short duration. Recently, remote sensing with satellite altimetry has provided a global view of sea level variations in the open ocean.

Sea ice conditions have been observed for long periods of time at selected coastal stations and by military or other special purpose ships. Global satellite-based coverage has only begun in recent decades, and documenting changes in sea ice is difficult because of changes in satellite instrumentation.

Surface winds are measured by NOAA's Automated Surface Observing System (ASOS), but these data are of limited use for monitoring decadal changes because of many inadequately documented changes in locations and measurement methods (Karl and Knight, 1997).

Sea level pressure measurements have a long history and can be used for approximating winds using first order physical relationships. The estimation of strong winds associated with both tropical and extra-tropical storms suffers from many problems. Typically, analysis methods, including model reanalyses and data availability, underestimate storm strength by an amount that varies over time.

NOAA satellites using the Advanced Very High Resolution Radiometer (AVHRR) sensor measure changes in vegetative cover. This data set spans three decades, but it is subject to biases, including unknown effects of natural and anthropogenic aerosols. There are many other promising technologies and observing systems becoming available to measure other aspects of land-cover change and biogeochemistry, but the record is too short to assess their performance for monitoring multi-decadal changes.

4. What characteristics should an observing system possess to provide useful climate data?

A complete discussion of the observing systems is contained in *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1998b); a distillation of the major points is included here for completeness of the present report.

Observational systems are composed of an entire sequence of process steps. An observing system is operational for climate purposes only if this entire sequence exists in a robust condition. The present study assesses the condition of the physical measuring system for a given variable and the characteristics that turn a set of measuring devices into a climate observing system.

A climate observing system should have the following characteristics:

1. measurements are taken with accurate, calibrated instruments and converted into geophysical data and stored;

2. data are collected and quality controlled;
3. data are put in standard format and compiled into useful data products; and
4. data and metadata[1] are stored in a repository that is readily available to users.

Additionally, for such an observing system to be useful for detection of climate trends and attribution to a cause, the resulting data sets must:

1. be precise and accurate enough for the early detection of trends over the next decade or so, and for continued monitoring;
2. be homogeneous in location, time, and method;
3. be long enough and uninterrupted in time for decadal trends to be resolvable; and
4. have sufficient spatial coverage and resolution to allow spatial patterns and their time dependence to be evaluated.

The concept of homogeneity introduced above depends on quality climate observations. A homogeneous data base contains no discontinuities introduced by a change in instrument location, human-induced environmental changes in the immediate vicinity of an instrument, an undocumented change in instrumentation, an uncorrected change in instrument calibration or other operating procedures, uncorrected instrument drift, or any other change that is an artifact of changing the measurement technique. Any data base obtained from an observing system not specifically designed and operated for climate observing purposes is likely to contain inhomogeneities that must be removed before the data can be used with confidence for climate analyses.

For any network or instrument whose mission is documentation of weather and climate, the following ten climate monitoring principles should apply (Karl et al., 1995). If followed, managers of operational and research observing systems can produce truly useful climate data. These principles provide a template for assessing the usefulness of a network for documenting climate variability and change. Moreover, they provide a management checklist for guiding all instrumental climate data-gathering activities.

[1]Metadata are the complete descriptions of how the observations were made. This includes the instrument employed, its calibration procedure, the observation protocol employed, the instrument platform, the surrounding physical and biological environment, measures to ensure the quality of the data, and data processing and storage procedures, including all changes in these factors over time.

CLIMATE MONITORING PRINCIPLES

1. **Management of Network Change:** Assess how and the extent to which a proposed change could influence the existing and future climatology obtainable from the system, particularly with respect to climate variability and change. Changes in observing times will adversely affect time series. Without adequate transfer functions, spatial changes and spatially dependent changes will adversely affect the mapping of climatic elements.
2. **Parallel Testing:** Operate the old system simultaneously with the replacement system over a sufficiently long time period to observe the behavior of the two systems over the full range of variation of the climate variable observed. This testing should allow the derivation of a transfer function to convert between climatic data taken before and after the change. When the observing system is of sufficient scope and importance, the results of parallel testing should be documented in peer-reviewed literature.
3. **Metadata:** Fully document each observing system and its operating procedures. This is particularly important immediately prior to and following any contemplated change. Relevant information includes: instruments, instrument sampling time, calibration, validation, station location, exposure, local environmental conditions, and other platform specifics that could influence the data history. The recording should be a mandatory part of the observing routine and should be archived with the original data. Algorithms used to process observations need proper documentation. Documentation of changes and improvements in the algorithms should be carried along with the data throughout the data archiving process.
4. **Data Quality and Continuity:** Assess data quality and homogeneity as a part of routine operating procedures. This assessment should focus on the requirements for measuring climate variability and change, including routine evaluation of the long-term, high-resolution data capable of revealing and documenting important extreme weather events.
5. **Integrated Environmental Assessment:** Anticipate the use of data in the development of environmental assessments, particularly those pertaining to climate variability and change, as a part of a climate observing system's strategic plan. National climate assessments and international assessments, (e.g., international ozone or IPCC) are critical to evaluating and maintaining overall consistency of climate data sets. A system's participation in an integrated environmental monitoring program can also be quite beneficial for maintaining climate relevancy. Time series of data achieve value only with regular scientific analysis.
6. **Historical Significance:** Maintain operation of observing systems that have provided homogeneous data sets over a period of many decades to a century or more. A list of protected sites within each major observing system should be developed, based on their prioritized contribution to documenting the

long-term climate record.

7. **Complementary Data:** Give the highest priority in the design and implementation of new sites or instrumentation within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution. Data sets archived in non-electronic format should be converted for efficient electronic access.
8. **Climate Requirements:** Give network designers, operators, and instrument engineers climate monitoring requirements at the outset of network design. Instruments must have adequate accuracy with biases sufficiently small to resolve climate variations and changes of primary interest. Modeling and theoretical studies must identify spatial and temporal resolution requirements.
9. **Continuity of Purpose:** Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.
10. **Data and Metadata Access:** Develop data management systems that facilitate access, use, and interpretation of data and data products by users. Freedom of access, low cost mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.), and quality control should be an integral part of data management. International cooperation is critical for successful data management.

At the present time USGCRP agencies lack the capability to routinely assess and, therefore, expeditiously correct problems related to multi-decadal climate and weather monitoring. These agencies operate a large number of observing and data management systems used by the scientific community, but no agency has the mission or assumes responsibility to assess routinely the adequacy of these data for analyzing decadal climate changes and variability.

A reliable and stable climate observing system is possible only if there are measures that assess its actual climate monitoring performance (i.e., near-real time assessment of data quality, continuity, and homogeneity). Through real time monitoring of these performance measures:

1. priority can be effectively established to meet the national needs for climate monitoring,
2. observing programs can be monitored for efficiency and data quality,
3. deficiencies can be identified, and
4. corrective action can be taken, including generating integrated programs and defending them through the budget process.

The use of such performance measures can minimize the need for subsequent data archeology and data homogeneity efforts when attempting to reconstruct the past climate record.

5. How good are existing observing systems at documenting climate variability and changes?

Existing observing systems for the relevant climate variables can be assessed using the ten principles for climate monitoring systems described above. Table 2 provides a summary of U.S. capability to monitor multi-decadal trends for each of the variables based on current and past performance in adhering to the principles of long-term climate monitoring. The table represents a panel consensus in applying the criteria described by the ten monitoring principles.

There are many deficiencies in each of the observing systems. Of those variables that have high priority for detection and attribution issues, surface temperature over the marine environment and sea surface temperature, vertical distribution of temperature, and water vapor have the most deficiencies. For these three variables, all principles but one are applied poorly. Those variables that have high priority for impact assessment—sea level pressure, winds, and precipitation—receive a similarly poor score.

6. Should we be concerned about our ability to document climate variability and change?

Clearly, based on the summary Table 2, there are many reasons for concern about our ability to document climate variability and change. The application of nine of the ten principles of climate monitoring needs improvement. How is it, then, that we are able to say anything about past climate variability and change? The research community has made use of observational data obtained for other purposes. Additionally, the networks changed at a relatively slow rate in recent decades, and had a primary focus on low-tech, human-intensive observing methods.

Unfortunately, at a time when major policy decisions regarding climate change issues are being made, the ability to observe the climate is disorganized and declining. Figures 1-4 show the decline in the data sets for the Historical Climatology Network (HCN), both global and national; the Comprehensive Aerological Reference Data Set (CARDS); and the Comprehensive Ocean/ Atmosphere Data Set (COADS).

During periods of budgetary austerity, reduced usefulness for long-term (multi-decadal) climate monitoring is too often the collateral damage suffered from prioritization of observing system requirements. The sponsor's primary interest is to serve the purpose for which an observing system was established. As a "free rider" in an economic sense, the climate research community has little influence in maintaining critical observing systems for long-term monitoring when budgets are reduced.

Changes in observing technology are also a threat to the homogeneity of the climate record. The effects of an instrument change in the Cooperative Observing Network are illustrated in Figure 5.

TABLE 2 Evaluation of capability to deliver data suitable for detecting climate variations and changes on multi-decadal time scales.

	PRINCIPLES											IMPORTANCE	
	1	2	3	4	5	6	7	8	9	10	TOTAL	DET	IMPACT
Temperature													
Surface land	--	--	--	A	A	--	A	--	A	A	5	H	H
Sea surface	--	--	--	--	A	--	--	--	--	--	9	H	H
Subsurface ocean	--	--	--	--	A	--	--	A	A	--	7	M	H
Vertical distribution	--	--	--	--	A	--	--	--	--	--	9	H	L
Water													
Land precipitation	--	--	--	--	A	--	--	--	--	--	9	M	H
Ocean precipitation	--	--	--	--	--	--	--	--	--	A	9	M	L
Streamflow	--	--	--	A	A	--	A	--	--	A	6	L	H
Evapotranspiration	--	--	--	--	A	--	--	--	--	A	8	M	H
Ground water	A	A	A	A	A	--	--	--	--	A	4	L	H
Snow cover/depth	--	--	--	--	A	--	A	--	--	A	7	L	H
Lakes and reservoirs	--	--	--	--	A	--	--	--	A	A	7	L	H
Atmospheric water vapor	--	--	--	--	A	--	--	--	--	--	9	H	M
Sea level	--	--	A	A	A	--	--	A	--	A	5	M	H
Sea ice	--	--	--	--	A	--	--	--	--	--	9	L	M
Sea Level Pressure and Winds	--	--	--	--	A	--	--	--	--	--	9	M	H
Terrestrial Ecosystems													
Land cover change	--	--	--	--	A	--	--	A	A	--	7	L	H
Biogeochemistry	--	--	--	--	A	--	--	A	A	--	7	L	H

Observation of items identified with '--' indicate known serious deficiencies, whereas observation of items identified with 'A' are adequate. Variables listed are covered in the report and are delineated by observing platforms whenever feasible. Abbreviations: DET = detection and attribution of change; IMPACT = impact assessments; H = high, M = moderate; and L = low. These values are the same as in Table 1. TOTAL is the sum of serious deficiencies.

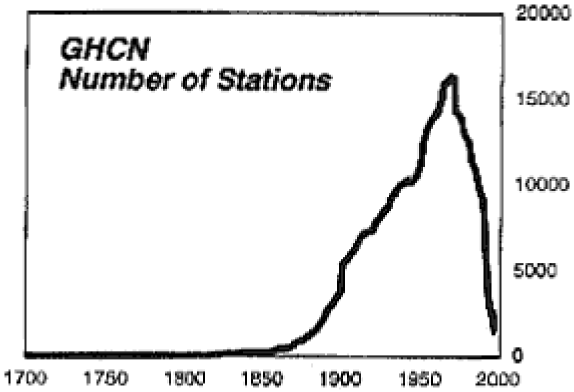

FIGURE 1
The Global Historical Climatology Network. Updated monthly from thousands of global stations, this data set provides monthly land surface data for temperature (maximum, minimum, and mean), precipitation, and pressure, adjusted for artificial discontinuities. This graph represents those stations that are being received at the National Climatic Data Center (NCDC) of NOAA. If substantial data recovery efforts are undertaken, NCDC expects that as many as half of the missing reports could be recovered.
SOURCE: NCDC, NOAA.

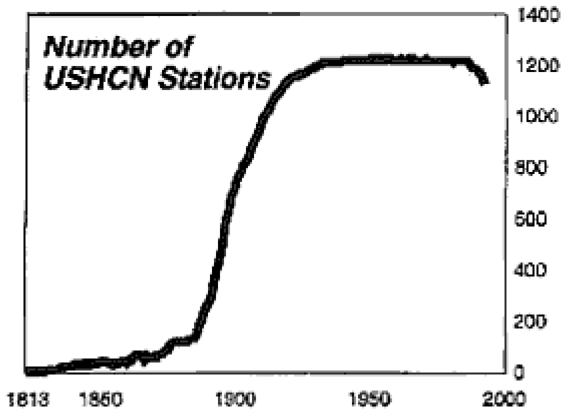

FIGURE 2
The U.S. Historical Climatology Network. This figure shows the number of stations in the U.S. historic network, officially identified in 1987, and already shows a significant decline beginning in the 1990s. SOURCE: NCDC, NOAA.

FIGURE 3
The Comprehensive Aerological Reference Data Set. CARDS consists of twice-daily radiosonde data sets providing global temperature, pressure, height, humidity, and wind. It also contains station histories, metadata, and information on bias detection. The period of record begins in 1948. SOURCE: NCDC, NOAA.

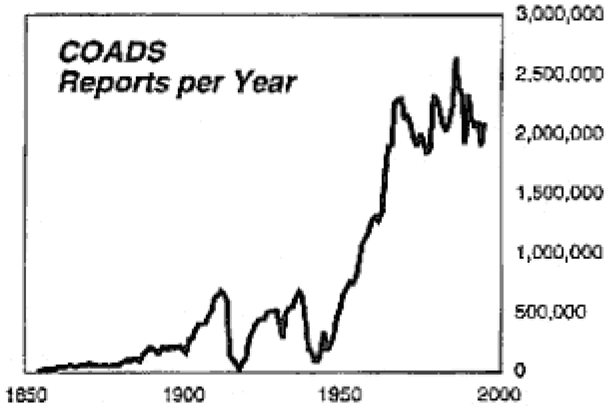

FIGURE 4
The Comprehensive Ocean/Atmosphere Data. COADS consists of data from ship and buoy observations of air and sea temperature, pressure, humidity, wind, wave, clouds, and past and present weather since 1854. Even with the addition of the ocean buoy programs in recent years, the number of reports is declining. SOURCE: NCDC, NOAA.

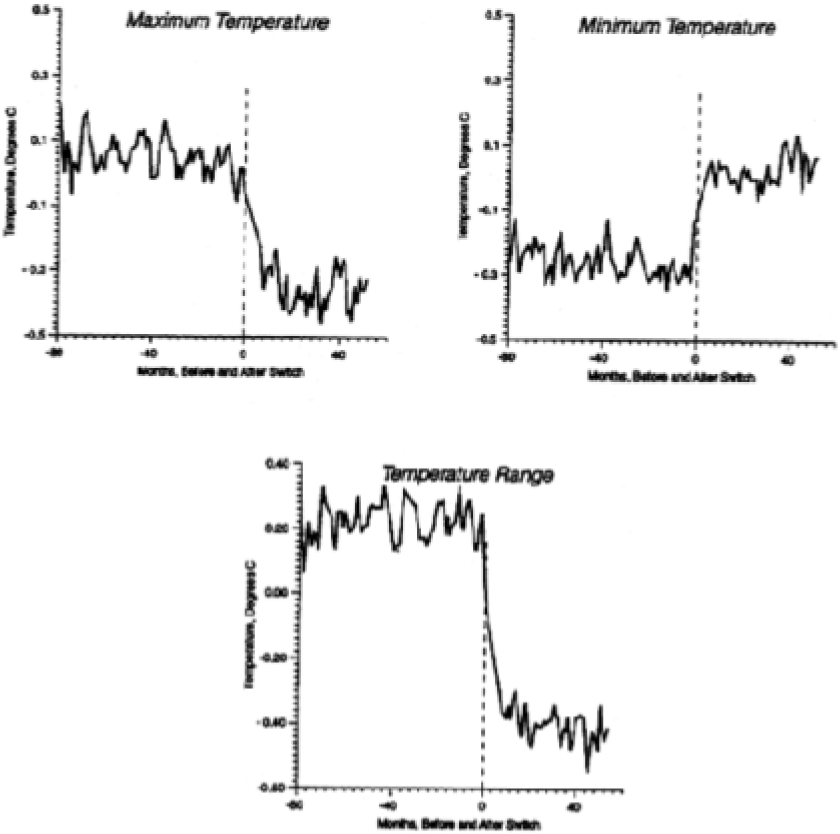

FIGURE 5
The effect of the change in instrumentation on the data for maximum, minimum, and range of temperatures of the Cooperative Weather Observer Network. These data represent the average time series of aggregated mean temperature differences referenced to the time of instrument change. The zero month is the month when the new observing technology was installed. SOURCE: NCDC, NOAA.

Historically, new demands for high-quality data for improved weather predictions and related data for understanding climate change have exceeded the capability of current operational systems. In past decades, climate was viewed as a stable entity at each specific location, and the needs for data were tied to defining and describing this perceived stationary climate. Climatologists calculated 30-year climate averages and variances from a suite of variables collected to help forecast the weather. Today, we understand that the climate is a dynamic, chaotic, changing system, and at times sensitive to small changes in forcing. It is no longer easy to accommodate the needs of climatologists with data from operational systems. Climate observing systems must provide data with enough fidelity, not only to know whether the climate is changing, including its extremes, but also to discern any acceleration or deceleration. Of particular interest are spatial patterns of change, including the vertical component. The details of climate change and variability have become critical tools for identifying specific forcings that may be responsible for the changes.

Major advances in technology and communications have provided opportunities for those responsible for developing, operating, and disseminating data and products derived from weather and environmental monitoring networks. Short-term forecasting efficiency has been increased by integration of this new technology. Unfortunately, its implementation has degraded significantly the continuity of long-term observing efforts which are so important to discerning changes in climate. In summary, these observing systems, which are critical for documenting climate change, are not suitably designed, operated, or maintained to meet the challenge before us.

7. What are the immediate roadblocks to continued development of a reliable record of climate variability and change?

It is essential to operate observing systems that are critical for building the data record of climate variability and change to achieve two objectives: (1) preserve the value of the past climate record and (2) build a more valuable climate record over future years. Operational decisions today have an immediate effect on the strength of the bridge that connects the past to the future. The future value of those observations will be proportional to the care one takes to relate them to observations taken in the past. Homogeneity of the observational climate data base should be a prime consideration in managing the operations of these systems and guiding their evolution.

Concern over the continued integrity of nearly all the observing systems analyzed in this study is warranted, and throughout this section, explicit examples are cited in the shaded boxes. Box 1 describes a generic problem for many of the climate variables measured in the United States.

Five systems of special concern and interest include those for marine surface air and sea surface temperatures, vertical distribution of atmospheric temperatures, precipitation, atmospheric water vapor, and sea level pressure and winds.

BOX 1 AUTOMATED SURFACE OBSERVING SYSTEM IMPACT ON CLIMATE RECORDS

The Automated Surface Observing System records have been corrupted by: (1) station relocations without suitable overlap between new and old stations, thereby lacking appropriate transfer functions; (2) changes in instrument algorithms and observing procedures without overlap between old and new methods; (3) discontinued observations of some key climate variables; (4) urban heat island effect and jet exhaust; (5) changes in local conditions; and (6) new instruments that were not calibrated with previous equipment. For example, in a recent assessment of the 1995 heat wave in Chicago where well over 500 people died, trends of temperature extremes could not be adequately assessed (Karl and Knight, 1997).

Marine Surface Air and Sea Surface Temperatures: Thorough documentation of past and current ocean surface observation techniques is required to reduce the possibility of inhomogeneities. Additional effort is required to link the results from several observation methods, including remote sensing, transient ocean ships, buoys, and floats. The marine environment is undersampled in both space and time, with data voids that challenge analysis techniques. Even current sampling is eroding, with losses in XBTs and surface drifters. Figure 4 illustrates the decay in the complete COADS data set within the last decade. Box 2 describes transitional problems associated with the ocean observations.

Vertical Distribution of Atmospheric Temperatures: New techniques are emerging to support more highly detailed weather forecasts. As these new techniques are introduced, considerations of apparent redundancy and budget pressures could shrink substantially the radiosonde network, which has provided our current understanding of global temperature variability and change over the last half century (see Box 3). Managing the transition to a new system should be planned and implemented carefully so that the historical data based on the radiosonde is not degraded (see Box 4).

Likewise, the value of data acquired in the future should not be diminished by inattention to linking with past data. Additionally, budgetary pressures to reduce the cost of operating and modernizing this system continue to place data continuity at risk, and to have a substantial adverse impact on the global network. Satellite data used to derive temperature profiles have been fraught with a lack of vertical resolution, as well as inhomogeneities caused by a failure to calibrate instruments.

Precipitation: High frequency precipitation measurements required for analysis of extreme precipitation rates are in danger of being permanently lost (see Box 5). Technology to read output from over 2,500 precipitation gauges in the United States is out of date, and replacement parts are no longer available. The long-term precipitation record at high latitude stations, where frozen precipitation is common, is plagued by instrument biases. If necessary actions are not taken to correct these deficiencies, the ability to identify precipitation changes that have an enormous impact on ecosystems and infrastructure throughout the United States will be seriously eroded.

Use of WSR-88D Doppler radar has been very limited because of deficiencies in access, calibration, and metadata. Measurements over the ocean must be blended from a variety of sources, but there is no federal plan to provide data in a reliable, continuous, and homogeneous manner. The NASA Tropical Rainfall Measurement Mission (TRMM) program has shown some promise, and a planned follow-on mission could result in a better sampling of the precipitation over the oceans.

Atmospheric Water Vapor: Water vapor is the most important greenhouse gas, and changes in it play a very important role for quantifying the effect of the addition of anthropogenic greenhouse gases into the atmosphere. It is also critical to understanding changes in the hydrologic cycle of evaporation, precipi

BOX 2 TRANSITIONAL PROBLEMS FOR THE ENSO OBSERVING SYSTEM

The NOAA tropical Pacific buoy program was funded (through 1997) through the NOAA Global Change Program. The NOAA Office of Oceanic and Atmospheric Research (OAR) now provides a sizable portion of the funding. This program may still not be sustainable for climate change detection purposes for two reasons. First, inflation is not built into the project budget, which may force short-term priorities to take precedence over long-term needs. Second, engineering development for the program was not initially funded. Recent decisions within NOAA, however, have allocated funds to this activity. While this is a positive development, the observations being made (parameters, frequency, precision, etc.) are determined by the requirements of the ENSO prediction mission of the observing system; thus, technological and other changes in the system are, primarily, made in response to these requirements. The long-term climate monitoring role is not currently a part of the data requirements.

tation, and surface runoff. At the present time, the United States is not adequately measuring high and low ranges of relative humidities. This is especially important near the tropopause. The implications of this deficiency are large; the magnitude of any global temperature increase is heavily dependent on the amount and distribution of water vapor.

BOX 3 RADIOSONDE DEFICIENCIES

The radiosonde, carried aloft on a balloon, dates from the mid-1920s as a viable tool for measuring variables in the upper atmosphere, and has been deployed extensively since the 1930s (Reed, 1977). Global networks with reasonable coverage, however, date from only the late 1940s and early 1950s. The organization and management of these networks received a major boost in 1962 with the inception of the World Weather Watch under the auspices of the WMO. Trenberth (1995) notes that the maximum coverage occurred during the period of the Global Weather Experiment (around 1980). The number of daily launches is now half of what it was in 1980. Sites have been closed and the frequency of launches from each site reduced to at most twice per day. The former USSR, for example, began closing sites in the early 1990s, and in the mid-1990s reduced launches from 4 to 2 per day. In North America, Canada has already closed some high-latitude sites, and is likely to close others. In 1985, budget pressures forced the NWS to close the remote stations at Barter Island, Alaska, and Wake Island in the Pacific. The loss of the more remote stations leaves large gaps in the geographic coverage and increases the ambiguity of the resulting climate record. Other major problems with the radiosonde network have been noted by Hurrell and Trenberth (1998) who pointed out that the radiosonde record is made up of differing instruments, with non-overlapping changes in the instruments over time, discontinuous records, and lack of sufficient metadata.

Sea Level Pressure and Winds: Managers of operational sea level pressure and wind measuring systems for weather forecasting continually change their practices to improve efficiency and accuracy. These changes have not been implemented in a manner that would allow the impact of change to be quantified in analyses. The importance of continuity of measurement is critical for identifying real climatic trends, such as possible changes in intensity, frequency, or location of major tropical and extra-tropical storms.

BOX 4 UNINTENDED CONSEQUENCES OF POLICY DECISIONS

Since 1958, the National Weather Service has used radiosondes from several suppliers, but the same sonde was used for an extended period of time. This changed in the mid-1980s when the change in Federal Procurement Regulations stressed the increasing need for competition in agency procurements. This resulted in a split contract award to two vendors. The homogeneous upper air network over the United States was lost without consideration of the impacts that the action had on the climate record. Metadata records (sonde types, sensor characteristics, calibration, etc.) are kept but have gaps, even for the U.S. sondes over this 40-year period. Trenberth (1995) provides a chronology of some of the changes in sensors, sonde design, calibration procedures, and data processing that have occurred in U.S. radiosondes.

BOX 5 PRECIPITATION MEASUREMENTS

The World Meteorological Organization has implemented a precipitation intercomparison study (Yang et al, 1995). NOAA, which operates the most extensive in situ networks, has failed to actively participate in these studies. Moreover, at the present time primary first order stations in the Automated Surface Observing System have failed to measure solid precipitation, and have introduced large time-dependent biases in the precipitation records (McKee, 1998). These biases are so great that they may have permanently corrupted the century-long precipitation measurements from several hundred stations across the United States. Ongoing research has verified that automated gauges have not performed adequately during many heavy precipitation events and most solid precipitation events (McKee, 1998). A modified gauge and interim solutions have been developed to help alleviate the problem, but the interim solution for precipitation measurements has resulted in a number of estimated precipitation measurements. False reports of precipitation are also still evident (McKee, 1998). Perhaps most disheartening are the specifications for the new automated instrument which indicate that a bias of up to 4 percent is acceptable. This is about half the estimated increase in U.S. precipitation over the twentieth century (Karl and Knight, 1998).

2

Findings and Recommendations

Scientific analysis of the issues relative to detecting climate change, attributing causes to that change, and evaluating the consequences of projected climate change all require a robust, credible climate observing system. Observing systems are in place that partially fulfill the requirements for meeting these objectives, but the continued viability of some of these systems is questionable. **Without immediate action to prevent the deterioration of some essential observing systems, the ability of the climate research community to provide over the next decade the objective scientific information required for informed decision making will be seriously compromised.**

In the longer term, a new paradigm of observing and data management systems for the purposes of detecting and attributing climate change is required. The central purposes of the USGCRP cannot be achieved with limited-duration research observations supplemented with operational observing and data management systems whose mandate does not make long-term climate change observations a critical responsibility. **Resolution of this problem requires those USGCRP agencies that operate observing systems expand the objectives of these systems to include climate observations as an equal partner with other operational requirements. A thorough review of procedures for operations and system changes should be made for each operational system to ensure that climate observing objectives are adequately served. Failure to pursue this recommendation will result in the continued struggle by USGCRP and other decision makers to distinguish between real observed climate change and artifacts produced by inadequate observing systems and data management practices.**

The ten Climate Monitoring Principles should be implemented as a

matter of priority. The systems' performance should be monitored with corrective actions implemented as necessary. All these actions will require funding to ensure that the climate mission is a significant component of the work of all relevant operational agencies.

FINDING: There has been a lack of progress made by federal agencies responsible for climate observing systems, individually and collectively, in developing and maintaining a credible, integrated climate observing system, consequently limiting the ability to document adequately climate change.

RECOMMENDATION: To remedy this situation, it is essential that these agencies work through the USGCRP process and at higher government levels to accomplish the following actions:

- ***Stabilize the existing observational capability***. In some instances, stabilization means nothing more than providing sufficient funding to continue programs. In others, substantial modernization of capabilities is essential because of both obsolescence and technological change. In still other instances, new capabilities are necessary to replace those lost in the recent past. Some stabilization will be relatively inexpensive (e.g., ensuring that climate records are accessible for processing), while others will require major funding (e.g., providing adequate definition of ocean variables or atmospheric water vapor).
- ***Identify critical variables that are either inadequately or not measured at all.*** Modeling and other theoretical studies are required to determine the adequacy of the spatial and temporal resolution required for observations of the critical variables. It is also essential to specify changes and variations at the appropriate spatial and temporal resolution for any additional climate variables that could provide society with the capacity to assess its vulnerability to climate variability and change, and to evaluate alternative adaptive measures.
- ***Build climate observing requirements into the operational programs as a high priority.*** Operational observation networks continue to be the backbone of climate measurements; significant parts of the climate observing requirements could be satisfied by these networks with only modest incremental costs. It is clearly not realistic to duplicate the global radiosonde network or the system of environmental satellites to provide a system dedicated solely to climate observations. Infrastructure support for these networks, including communications, procurement, and management, is most cost effective when consolidated into dual-use operational systems. However, the existing operational networks, while essential, are not sufficient for climate purposes: there are serious deficiencies both in the variables measured and the time and space scales employed. Moreover, climate needs do not receive sufficiently high priority by operational system managers to survive the effects of inevitable

technological changes. Continuity, consistency, and homogeneity are essential for climate observations, but they have not been a priority for operational networks. Climate requirements that are not being satisfied should be incorporated into the operational programs as the most overall cost-effective solution.

- ***Revamp climate research programs and some climate-critical parts of operational observing programs.*** The ten principals for climate observation should be implemented. If the principles are followed, managers of operational and research observing systems can produce truly useful long-term climate data.
- ***Establish a funded activity for the development, implementation, and operation of climate-specific observational programs.*** Such an activity has two parts: (1) providing essential additional capability to operational observing systems and (2) generating a specialized climate observing capability.

The first part augments operational programs to ensure that data used for climate have the quality, coverage, resolution, continuity, timeliness, and stability required for climate change detection and attribution. This should include adequate studies of data requirements, including spatial and temporal resolution, as well as the required data assimilation studies. Additional variables should be added to the operational suite as needed (e.g., new or enhanced radiometers or data processing).

The second part provides for observing capabilities specific to climate, as a part of existing networks, if possible. This should include, for example, the sampling of trace gases distributed throughout the atmosphere; use of reference radiosondes at specified times and locations; identification of a subset of baseline; and reference stations from a larger network for special operating procedures. To the extent possible, this specific climate observational capability should be integrated into existing networks so that a cost for establishing and operating a parallel network is not incurred.

In the near term, the USGCRP agencies can ameliorate this situation by taking the following actions:

1. All agencies operating climate-relevant observation systems should adopt and implement the set of Climate Monitoring Principles outlined in question 4.
2. System performance measures should be developed and monitored on a regular basis. It would be unwise to wait for a major environmental assessment or data archeology effort to discover that problems that occurred 10 or 20 years earlier had already inflicted considerable damage on the climate record. An institutional infrastructure should be developed to assess the quality of data sets and correct problems as they occur.
3. Accelerate access by the research community to climate-related observation data bases, primarily in non-electronic formats, that reside deep in agency archives.

4. The free, open, and timely exchange of data should be a fundamental U.S. governmental policy and, to the fullest extent possible, should be enforced throughout every federal agency that holds climate-relevant data. Adherence to this principle should be promoted more effectively by the U.S. government in its international agreements, with particular attention given to implementation.
5. Vastly improved documentation of all changes in equipment, operations, and site factors in operational observing systems are required to build confidence in the time series of decadal-to-centennial climate change.
6. Establish and maintain strong, robust links between operational systems managers and the climate data users.
7. Because U.S. economic and social interests depend on knowing the climate globally, U.S. agencies should pursue international cooperation in climate observation and monitoring through international mechanisms. USAID funds may be one vehicle to ensure critical observations in developing countries.

3

Concluding Remarks

The climate research community relies on a number of disparate observation systems to assemble a data base that it uses to analyze climate variability and change. A few of these systems function reasonably well, but for most, there are clear warning signals that must be heeded if climate variability and change is to be observed with sufficient fidelity over the next decade or two.

It is insufficient to evaluate in isolation the status of individual climate observing systems, rather they should be evaluated on how well they form a comprehensive, integrated climate observing system. Today, no one agency has claimed a primary mission of long-term, homogeneous climate observations. The evidence leads to the conclusion that this is an ancillary activity for all agencies involved in observations. Moreover, the USGCRP has neither the charter nor the ability to compel agencies to support programs they have failed to embrace. The consequence of these factors is that the institutional environment for developing and maintaining a credible, integrated climate observing system does not exist.

This panel was not given the mandate for advising the USGCRP on how it should address this fundamental problem. Scientists can assist in evaluating the merits of proposed alternative solutions, but there are many non-scientific aspects of an institutional nature that will determine the choice of an ultimate solution. However, the panel believes the USGCRP, or its parent, CENR, should consider developing and adopting a strategic plan containing alternative options that would be responsive to resolving this problem. It could incorporate the involvement of administrators at appropriately high levels, including OSTP and OMB, to adopt or, if required, to seek Congressional approval for changes in agency objectives and programs.

Until this issue has been addressed, the existing observation systems for climate variables should be maintained. Those agencies that manage operational systems for weather forecasting and other societal purposes, and those agencies that operate longer-term research networks need to exercise increased stewardship over those aspects of their operations that contribute to a homogeneous climate data base. These agencies should resist budgetary pressures and other factors that erode the climate value of observations. The funds required to maintain the value of observations for climate detection and attribution are a few percent of the total operating cost of the existing operational and research systems and are usually incurred in the initial design considerations.

Additionally, the USGCRP should note that even though some observing systems have been maintained in a research mode for many years, continuity of these observations is not assured because they satisfy no ongoing operational requirement and are therefore subject to the vagaries of research funding. The following example came to the panel's attention as the report was being completed. NOAA recently reduced the operation of ozonesonde launches at the South Pole. The sonde operation was funded by satellite calibration and validation efforts and was operated by NOAA's research arm. Budget pressures on the satellite programs resulted in the natural process of reducing the lower priority activities. Although NOAA's research arm is attempting to piece together enough funding to continue a reduced sonde operation, several scheduled soundings have been missed, and the 18-year record of this important trace constituent at the South Pole is now in extreme jeopardy. To develop and maintain an integrated climate observing system, the USGCRP should develop a long-term strategy that identifies observing systems and schedules to transform research systems into an operational status. The technical and institutional steps necessary to transform a research observational system into operational status should be carefully considered to preserve the homogeneity of each data record.

Because of the panel's task and time available, this report considered only existing observing systems. The panel would be remiss, however, if it did not identify concerns about the potential impact of agency plans and initiatives. If implemented incorrectly, these plans could greatly change the observing programs over the coming two decades with a concomitant, and largely unknown, impact on the climate record. As long as climate activities rely mostly on operational networks that do not recognize climate data requirements, those agency plans and initiatives will be of fundamental concern to the climate community.

The growing emphasis on operational mesoscale observations and forecasts inevitably will lead to a growing reliance on remote sensing—both surface- and space-based. If, in the process, existing in situ networks, such as the radiosonde, are reduced in size or importance, there could be a large negative impact on the ability to assess climate and climate change. The panel recognizes that many of the atmospheric observations in ocean areas can be provided only by global systems such as satellites. At the moment, however, only sketchy information exists on the suitability of remotely sensed data as a source for climate change detection and attribution. Some studies have shown a positive impact of these data; others have clearly indicated substantial problems, two of which are calibration and poorly documented changes in the instrument performance from one satellite to the next.

This report notes the need to build climate observing requirements into the operational programs as a high priority. That need is especially important as observing networks rely even more on remote sensing. Climate requirements should be considered in the planning process. There should be sufficient funding to test and evaluate new data sources before implementation, and support should be given to developing the new data assimilation and related techniques needed to make the transition from current to future observing systems.

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Appendixes

Appendix A

Message from the 1997 Conference on the World Climate Research Programme to the Third Conference of the Parties of the United Nations Framework Convention on Climate Change

Well over 300 members of the climate research and policy communities present at the Conference on the World Climate Research Programme (WCRP) (Geneva, Switzerland, 26–28 August, 1997) agreed that comprehensive observations of the climate system are critical, and noted with concern the decline in conventional observation networks in some regions. This is a serious threat to continuing progress in climate research, and to detection of climate change and attribution of its causes. *Without action to reverse this decline and develop the Global Climate Observation System, the ability to characterize climate change and variations over the next 25 years will be even less than during the past quarter century. (emphasis added)* In some regions, for example, drought-prone parts of Africa, climate change detection, prediction of seasonal and long-term variations and reliable assessment of climate impacts could become impossible.

Recognizing the obligations of Parties to the United Nations Framework Convention on Climate Change under Article 4.1 (g) and (h) (Commitments) and Article 5 (Research and Systematic Observations), we strongly urge that, at the coming session of the Conference of Parties, arrangements be put in place to ensure funding and support for the essential observation networks of the Global Climate Observing System (GCOS) and its oceanographic and terrestrial counterparts, and for research involving data interpretation and analysis, as well as for retrieval and preservation of historical data in electronic form.

Without such support, future assessment reports of the Intergovernmental Panel on Climate Change (IPCC) which draw heavily on WCRP research and on the observational data sets, will be significantly compromised.

Appendix B

Relevant Sections from the Framework Convention on Climate Change

Article 2 Objective

The ultimate objective of this Convention.........(is the) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Article 4 Commitments

All parties, ..., shall: 1(g) Promote and cooperate in scientific, technological, technical, socioeconomic and other research, systematic observation and development of data archives related to the climate system and intended to further the understanding and to reduce or eliminate the remaining uncertainties regarding the causes, effects, magnitude and timing of climate change and the economic and social consequences of various response strategies; and

1(h) Promote and cooperate in the full, open and prompt exchange of relevant scientific, technological, technical, socioeconomic and legal information related to the climate system and climate change, and to the economic and social consequences of various response strategies.

Article 5 Research and Systematic Observation

In carrying out their commitments under Article 4, paragraph 1(g), the Parties shall:

(a) Support and further develop, as appropriate, international and intergovernmental programs and networks or organizations aimed at defining, conducting, assessing and financing research, data collection and systematic observation, taking into account the need to minimize duplication of effort;

(b) Support international and intergovernmental efforts to strengthen systematic observation and national scientific and technical research capacities and capabilities, particularly in developing countries, and to promote access to, and the exchange of, data and analyses thereof obtained from areas beyond national jurisdiction; and

(c) Take into account the particular concerns and needs of developing countries and cooperate in improving their endogenous capacities and capabilities to participate in the efforts referred to in subparagraphs (a) and (b) above.

Appendix C

Statement of Task

This study will examine the current and near-term prospective status of operational and research observing networks and related data systems that are essential to documenting climate variability and change. The proposed study will:

1) identify the data from observing systems that are critical for detecting and documenting secular trends and variability of relevant climate variables;
2) characterize the current status of these systems in terms of capacity to produce data products with sufficient spatial and temporal resolution, and adequate accuracy and precision, to document secular trends and analyze human attribution;
3) describe the historic trend in the status of each system over the past decade, and contemplated events that may change that trend over the near-term future, and analyze the implications of such trends for documenting climate change and attributing causation;
4) identify changes in the end-to-end observing system structure including operations, data processing, and data access that could affect the systems capability for documenting climate variability and secular trends, or analyzing human attribution; and
5) analyze opportunities to manage and apply resources so as to avoid adverse effects on the future scientific value of the climate database.

Appendix D

U.S. Global Change Research Program

October 14, 1997

Dr. Thomas Karl, Chair
Committee on Climate Research
Board on Atmospheric Sciences and Climate
National Research Council
2101 Constitution Ave., NW Washington, D.C. 20418

Dear Dr. Karl:

This is to follow-up on our several conversations regarding the "observing and related long-term database" issues. On behalf of the U.S. Global Change Research Program (US/GCRP), particularly DOE, NASA, NOAA, and NSF, we want to share with you and the Committee on Climate Research a growing concern we are observing over the stability of the observing and related long-term database systems upon which nearly all of our current understanding of recent and future climate and global change trends depends. An increasing number of global change and climate researchers seem to be voicing this concern over a perceived deterioration of some of the observing systems. Indeed, several recent reports of the World Meteorological Organization and the National Research Council have noted the need for concern.

It would be useful to the US/GCRP if the Climate Research Committee could conduct a rapid-response study (several months at the most) on this situation, particularly as it relates to observing capabilities and the long-term databases that they produce. To maximize the utility of such a study, we suggest that, if you and your Committee agree to undertake this task, the study should:

1) Identify the data from observing systems that are critical to detecting and documenting secular trends and variability in relevant climate parameters;

2) Characterize the current state of health of these systems in terms of capacity to produce data products with sufficient spatial and temporal resolution, and adequate accuracy and precision;

3) Describe the secular trend in the health of each system over the past decade, and contemplated events that may change that trend over the foreseeable future;

4) Identify changes in the end-to-end observing system structure including operations, data processing, and data access that diminish its value for documenting climate variability and secular trends; and

5) Identify data from observing systems that are clearly needed to clarify the potential human contributions to greenhouse gas forced climate change that are not being made by currently or planned operational systems.

Because the results of such a study would have their highest utility if they were produced in time to provide information for Congressional considerations during the FY 99 budget process and for the agencies' development of their FY 2000 budget proposals, having a report available by mid-March of next year would be the most helpful.

Ideally, the suggested study should be structured in an open manner that would allow the scientific community, members of the communities that utilize operational data, staff members from agencies, and Congressional committees and/or their staff to interact with the NRC scientists and professional staff performing the study. We recognize that, while the Climate Research Committee is well-constituted to undertake the climate portion of such a study, cooperation with other NRC units (CGCR, and the many related committees and boards) would be necessary to plan and perform the study. In the context of the five issues outlined above, we would appreciate the Committee's views on the status and progress of the longer-termed studies under way towards implementing the IGOS (your comments on the six candidate pilot projects would be particularly useful), GCOS, GOOS and GTOS, and the transition of how to get from where we are now to where these developmental international systems may take us in the future. Further, and as you know, the Board on Sustainable Development has long had plans to conduct a comprehensive study of the observing capabilities necessary to support our nation's long-term interests in global change and sustainability issues. Understanding their plans would also be important. Finally, in the context of interagency processes, there are four entities with whom you might wish to connect to determine their current plans: (I) the newly constituted US/GCRP Observing System Working Group (Bob Schiffer at NASA is the liaison for this group) and the US/GCRP interagency data and information management working group (Tom Mace of

EPA chairs this group-His e-mail is: MACE.TOM@EPAMAIL.EPA.GOV), (ii) the CENR Task Force on Observing and Data Management (Bill Townsend at NASA and Bob Winokur at NOAA co-chair this body) and (iii) the Environmental Monitoring Initiative (Jerry Melillo is the best contact for this initiative). They can give you insights as to their current plans within the Federal government. Most importantly, we would be interested in the Committee's recommendations concerning the highest priority measurements from those systems and any other systems (i.e., WWW) that must be sustained over multi-decadal time frames.

It is our view that it is critically important to interact with these domestic and international observing capabilities so that your "rapid-response study" connects their plans with the recommendations and directions you offer. So that we maximize the benefits from your efforts, we believe that this proposed study be more narrowly focused on climate observing and related long-term database issues and be conducted in the several months ahead. This approach, in our view, will assist the Federal agencies and the nation in addressing our more immediate climate change and variability observing/data requirements. We would expect that this study should give the US/GCRP and the participating agencies a thoughtful but rapid-response assessment of our nation's current plans for climate observing and related long-term database capabilities that will impact FY 1999 and FY 2000 plans.

This letter outlines a daunting task. We suggest that you scope the effort so that a useful product is produced in the available time. We look forward with interest to your response to the above suggestions. It is our understanding that such a study can be done as a priority task within the funding of the present award to the NRC from the US/GCRP. If there is a need to contact us to discuss this suggestion in further detail, please feel free to do so at: 703-306-1500 (NSF Office) or through e-mail at rcorell@nsf.gov.

Thank you and our committee for your willingness to consider this matter.

Sincerely,

(signed)
Robert Corell, Chair
Subcommittee Global Change Research
Committee on Environment and Natural Resources

cc: SGCR, William Townsend — NASA, Nancy Maynard — NASA, Robert Winokur — NOAA, Robert Schiffer — NASA, Tom Mace — EPA, Michael MacCracken - Office of the US/GCRP, David Goodrich — NRC

Appendix E

Decision 14/CP.4

Research and systematic observation

The Conference of the Parties,

Recalling Article 4.1(g) and (h), and Article 5 of the United Nations Framework Convention on Climate Change and its decision 8/CP.3,

Having considered the documents on the development of observational networks of the climate system submitted to it by the Subsidiary Body for Scientific and Technological Advice[1],

Noting with appreciation the comprehensive report on the adequacy of the global observing systems for climate prepared and coordinated by the Global Climate Observing System secretariat in the World Meteorological Organization on behalf of organizations participating in the Climate Agenda,

Noting the conclusions of the report that, inter alia, in many instances global and regional coverage is inadequate,

Noting the recommendations contained in the report to improve the global observing systems for climate,

Noting the ongoing work of the agencies participating in the Climate Agenda and others in support of global observing systems for climate, including their contribution to capacity-building,

Recognizing the significant national contributions made to the global observing systems for climate,

[1] **FCCC/CP/1998/7 and FCCC/CP/1998/MISC.2.**

1. Urges Parties to undertake programmes of systematic observation, including the preparation of specific national plans, in response to requests from agencies participating in the Climate Agenda, based on the information developed by the Global Climate Observing System and its partner programmes;
2. Urges Parties to undertake free and unrestricted exchange of data to meet the needs of the Convention, recognizing the various policies on data exchange of relevant international and intergovernmental organizations;
3. Urges Parties to actively support the building of capacity in developing countries to enable them to collect, exchange and utilize data to meet local, regional and international needs;
4. Urges Parties to strengthen international and intergovernmental programmes assisting countries to acquire and use climate information;
5. Urges Parties to actively support national meteorological and atmospheric observing systems, including measurement of greenhouse gases, in order to ensure that the stations identified as elements of the Global Climate Observing System networks, based on the World Weather Watch and Global Atmosphere Watch, and underpinning the needs of the Convention, are fully operational and use best practices;
6. Urges Parties to actively support national oceanographic observing systems, to ensure that the elements of the Global Climate Observing System and Global Ocean Observing System networks in support of ocean climate observations are implemented and, to the extent possible, support an increase in the number of ocean observations, particularly in remote locations, and to establish and maintain reference stations;
7. Urges Parties to actively support national terrestrial networks including observational programmes to collect, exchange and preserve terrestrial data according to the Global Climate Observing System and the Global Terrestrial Observing System climate priorities and particularly hydrosphere, cryosphere and ecosystem observations;
8. Requests Parties to submit information on national plans and programmes in relation to their participation in global observing systems for climate, in the context of reporting on research and systematic observation, as an element of national communications for Parties included in Annex I to the Convention (Annex I Parties) and, as appropriate, for Parties not included in Annex I to the Convention (non-Annex I Parties);

9. Requests the Subsidiary Body for Scientific and Technological Advice, in consultation with the agencies participating in the Climate Agenda, drawing, inter alia, on the information provided in the second national communications of Annex I Parties and, as appropriate, in the initial national communications of non-Annex I Parties, to inform the Conference of the Parties at its fifth session of developments regarding observational networks, difficulties encountered, inter alia, with respect to the needs of developing countries and options for financial support to reverse the decline in observational networks;
10. Invites the agencies participating in the Climate Agenda, in consultation with the Global Climate Observing System Secretariat, to initiate an intergovernmental process for addressing the priorities for action to improve global observing systems for climate in relation to the needs of the Convention and, in consultation with the Convention secretariat and other relevant organizations, for identifying immediate, medium-term and long-term options for financial support; and requests the secretariat to report results to the Subsidiary Body for Scientific and Technological Advice at its tenth session.

Adopted at the 5th Plenary Meeting
11 November 1998

Appendix F

Acronyms

ASOS	Automated Surface Observing System
AVHRR	Advanced Very High Resolution Radiometer
CARDS	Comprehensive Aerological Reference Data Set
CENR	Committee on Environment and Natural Resources
COADS	Comprehensive Ocean/Atmosphere Data Set
DOD	Department of Defense
ENSO	El Niño/Southern Oscillation
FAA	Federal Aviation Administration
FCCC	Framework Convention on Climate Change
GCOS	Global Climate Observing System
GOOS	Global Ocean Observing System
GTOS	Global Terrestrial Observing System
HCN	Historical Climatology Network
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PALACE	Profiling Autonomous Lagrangian Circulation Explorer
TRMM	Tropical Rainfall Measurement Mission
USAID	U.S. Agency for International Development
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
XBT	expendable bathy-thermograph