THE NEED FOR A SYSTEMS APPROACH TO CLIMATE OBSERVATIONS

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Because climate is changing, we need to determine how and why. How do we best track and provide useful information of sufficient quality on climate?

The most recent Intergovernmental Panel on Climate Change report (IPCC 2001) concludes, "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." The National Academy of Sciences report titled, "Climate Change Science" [National Research Council (NRC) 2001] reaffirmed the IPCC findings and, subsequently, President Bush outlined the Administration's climate policy on 11 June 2001. This new policy recognizes that climate is changing. It emphasizes the uncertainties that exist and calls for the establishment of a U.S. Climate Change Research Initiative "to study areas of uncertainty and identify priority areas where investments can make a difference." It also provides for "new resources to build climate observation systems and calls on other developed countries to provide matching funds, to help build climate observations in developing countries. . . ."

The ideas in this report were developed in part through information assembled from multiple sources in an effort to identify priorities to respond to President Bush's speech. We outline a strategic way of thinking about how observations should be gathered and used that emphasizes an integrated system. There is a need to set observations in the appropriate framework in order to obtain value from the data. A climate observing system must go beyond the climate observations themselves to include the processing and support system that leads to reliable and useful products. To be most effective it must also provide critical data for related areas such as weather forecasting, human health, energy, environmental monitoring, etc.

Recently, Goody et al. (2002) put forward a strategy on why it is important to monitor the climate. They focused on testing the predictive capabilities of climate models and the need for "benchmark" climate observations. The latter are data with high absolute accuracy (measured in a way that is independent of the local environment) but are still subject to temporal and spatial sampling errors. Here we put forward other critical considerations and justifications for a comprehensive climate observing system, in particular, emphasizing a systems approach to the processing, management, and care of the observations.

In situ data from all parts of the globe are essential to this system and often can only be garnered

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within a strong international framework through the United Nations, such as under the World Meteorological Organisation (WMO), the World Climate Programme, and the Global Climate Observing System (GCOS). The latter was established in 1992 as mandated by the Second World Climate Conference. In fact, various ideas in this report were developed in the context of GCOS. Nevertheless, the international GCOS, while able to develop requirements and provide advice regarding national efforts, presently does not have the resources to implement observing systems or effectively coordinate the resulting observations; these activities must be done by individual nations. We outline arguments to invigorate support for GCOS.

To advance the understanding of climate change and its forcings, it will be necessary to have a comprehensive global observing system reliably producing high-quality data and products. We describe here just such a comprehensive end-to-end system. Although the United States and international partners through national investments are developing elements of such a system, an overall integrated system is not in place. We believe steps should be taken to establish it. We further argue that the United States should play a leadership role in such an endeavor.

THE NEED FOR A REVITALIZED OBSERVING SYSTEM. The new and growing imperative for climate observations arises from the recognition of climate change needs. While the costs of a comprehensive climate observing system may appear to be a major obstacle, they are reasonable when placed in the appropriate context. In particular, the benefits are significant and make such a system worthwhile and cost-effective for many areas of planning and decision-making influenced by weather and climate.

For many practical considerations, it is appropriate to develop a suite of system components that will effectively and efficiently meet the needs for climate observations and, in addition, provide added benefits in dealing with other societally important issues. While observations are usually justified and paid for with a primary purpose in mind, all observations should serve multiple purposes. Observations made to monitor or forecast the weather or seasonal-to-interannual climate variability can, with more care, also help serve the needs for decadal variability and climate change.

Quite aside from their growing role in monitoring and modeling climate change, climate observations can be justified by their other applications. Many businesses, governments, and others use these observations, which include temperature, wind, humidity, soil moisture, and other climate state variables, to reduce climate-related risk in the protection of life and property as well as to enhance climate-related resources for economic prosperity and improved quality of life. Nevertheless, each year, the direct impacts of weather and climate conditions adversely impact the U.S. economy by tens of billions of dollars and cause hundreds of fatalities. For example, the information developed in climate atlases and "climate normals" provide users with site-specific information about the probability of freezes, heavy precipitation, high winds, frost depths, the amount of solar radiation received, and other factors. Among many uses, climate information is often used in the design of urban infrastructure such as construction, roads, water supply, and storm water routing; the efficient and safe operation of airports, communications technology, and power plants; and in the planning for marketing strategies and energy usage. For example, the American Homebuilders Association estimates that they have saved the public $300 million a year by promulgating a new building standard for foundation depths based on a new air-freezing index (Steurer 1996; Steurer and Crandell 1995). In another example, the weather risk industry has used in situ data to settle contracts traded on the Chicago Mercantile Exchange and billions of dollars have been traded in the "over-the-counter" markets. The health industry is actively assessing climate–health relationships. Insurance companies use weather and climate-related data to settle claims and the courts use the data in legal matters. Federal agencies also depend on data, for example, NASA, to design the operating conditions expected for the Space Shuttle, and the Federal Emergency Management Agency to assess the severity of extreme weather and climate events for federal emergency relief funds.

These multiple applications of climate data are in fact critical to a good observing system. Data can only be evaluated if they are compared and used. Moreover, the utility of the data for protecting life and property cannot be evaluated unless there are active research programs that examine the effects of climate variability and change on life and property.

Because climate change is of special concern now and into the foreseeable future, continuing, long-term data on climate is central to prudent stewardship of resources and the protection of life and property. Continuous environmental monitoring allows assessments of the risks of fires, floods, and other threats to the environment, public health, and the food and water supply, and these are all elements that relate to security. Without the capacity to monitor, measure, and predict changes in the climate system, policy makers and individual citizens alike will be forced to make long-term commitments and decisions related to vital issues without critical information. Access to long-term projections of climate change will improve economic decisions by corporations, state and local governments, and individual citizens. In short, the climate observing system will be an essential informational tool for everyone planning for and coping with climate change.

Therefore, regardless of whether or not the rate of human-induced climate change can be slowed, there is a compelling case for 1) improved description of changes as they happen, 2) better assessment of why the changes are happening (in particular the role of forcings, climate system inertia, and natural variability), and 3) developing the capability to produce reliable predictions of climate for several planning horizons into the future, ranging from seasons to decades.

CLIMATE MONITORING.

Climate research and monitoring require an integrated strategy of land–ocean–atmosphere observations, including both in situ and remote sensing platforms, modeling, and analysis. An adequate global climate observing system would be made up of instruments on various platforms, including ground stations, ships, buoys, floats, ocean profilers, balloons, aircraft and satellites, and samplers. The United States is an active and leading partner in the development and support of a global observing system that assembles key elements from a number of observing networks under the aegis of appropriate international organizations, in particular GCOS. Components for atmospheric, oceanic, terrestrial, and satellite observations are supported at varying levels depending on scientific priorities, availability of national contributions, and the sophistication of the relevant observing technologies. In addition to the internationally coordinated programs, numerous national observing efforts are directed toward understanding and predicting climate change, variability, and extreme events. Expansion of national systems to global scale through international cooperation should be a high priority.

Satellites provide the primary means of obtaining a global perspective and comparing different parts of the globe. A long global climate record is not practicable without a major satellite component. Recently, an Integrated Global Observation Strategy (IGOS) was formed to develop a comprehensive observing capability utilizing both space-based and in situ observing systems. IGOS partners the major satellite and global surface-based systems and links research, long-term monitoring and operational programs—as well as data producers and users—in strategic planning to identify the resources to fill observation needs. The IGOS partnership has emphasized space-based components of the observing system and includes the Committee on Earth Observing Satellites (CEOS); the global observing systems for climate, atmosphere, oceans, and land surface; their sponsors[1]; and the international science programs addressing global change [i.e., the World Climate Research Programme (WCRP) and International Geosphere-Biosphere Programme (IGBP)] and their funding agencies (the International Group of Funding Agencies for Global Change Research).

Shortcomings of the present system. These efforts have, by themselves, not been enough. The current climate monitoring system relies upon a mix of observations made for other purposes. In the atmosphere, most observations are made for weather forecasting and aviation without adequate consideration given to climate requirements. Climate monitoring requires a long-term commitment to quality and stability. As many of the climate-related signals are small relative to the day-to-day weather variability, small time-dependent changes in the observing system that are unimportant for weather can mask real and significant changes in climate. The practical goal of climate monitoring is to have consistent continuous data for long periods of time. Observations of climate must be more accurate than weather data because we are concerned with relatively small changes that are significant when viewed over decades or centuries. For example, significant global temperature changes are on the order of a few tenths of a degree Celsius per century, or important changes in cloud cover and distribution are a few percent.

Surface and in situ observations, often associated with weather networks, have provided the most important basis so far for the detection and attribution of causes of global climate change the (IPCC 2001). Surface data are also used in a variety of applications to reduce climate-related risk to life and property, and often act as anchor points for validating space-based measurements. For these reasons, the surface and in situ networks constitute an irreplaceable resource that operates under serious difficulties at a time when there

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[1] WMO, the United Nations Educational, Scientific and Cultural Organization, the Intergovernmental Oceanographic Commission, Food and Agricultural Organization, the United Nations Environment Programme, and the International Council for Science.

are increasing demands for a capable global observing network.

The many shortcomings to the current system relate to surface and upper-air atmospheric measurements, observations of atmospheric composition, global ocean, land surface (including surface hydrology, vegetation, soil moisture, ecosystems, and carbon inventories), and cryospheric variables. For example, only half of the GCOS Upper-Air Network (GUAN), established for climate purposes, has been reporting regularly in its first few years of operation, and the GCOS Surface Network (GSN) for climate has had similarly disappointing results. The ocean is poorly observed below the surface and large parts of the ocean have never been measured in some seasons (such as the Southern Oceans in winter). Over land, the great spatial heterogeneity requires extreme detail and is a major challenge.

Long-term consistency generally does not exist so, to produce continuity, heroic reconstruction attempts have to be made to quantify and minimize space- and time-dependent biases (e.g., for the radiosonde network see Gaffen 1994). For example, Quayle et al. (1991) estimate the bias introduced by switching sensors from thermometers to thermistors housed in different screens in the Cooperative Network (Fig. 1). Similarly, switching instruments in the U.S. primary observing network from the HO63 to the HO83 series (Fig. 2) changed the maximum temperature by about 0.5°C. Moreover, the current climate monitoring system is often incapable of providing critical information about both means and extremes (Karl et al. 1999; IPCC 2001) for several important phenomena.

Just as observing systems today are monitored for random errors and missing data, for climate a near-real-time system is required to monitor observing systems for time-dependent biases. Too often these biases are discovered years after the fact, when the record must be adjusted by statistical methods that often have either uncertain or rather large confidence intervals. The U.S. Climate Reference Network (Heim 2001), now being implemented by the National Oceanic and Atmospheric Administration (NOAA), provides a good example of why such real-time monitoring is critical. Figure 3 depicts the impact of a design problem of a water-related short in the thermistor cables, found using a planned set of redundant instruments, which was corrected within three days of its detection. Real-time monitoring of network performance is fundamental to a healthy climate observing system.

These problems are not limited to in situ observations. Likewise the extensive U.S. space-based, remote sensing observation program has shortcomings for climate observations. Operational observations from satellites have helped track climate change, but many are riddled with uncertain time-dependent biases. They are far from realizing their full potential to provide valuable information about multidecadal climate change because this has rarely been a priority of the satellite programs. The typical lifetime of a satellite is three to five years. Replacement satellites are likely to have a somewhat different orbit and sample a given

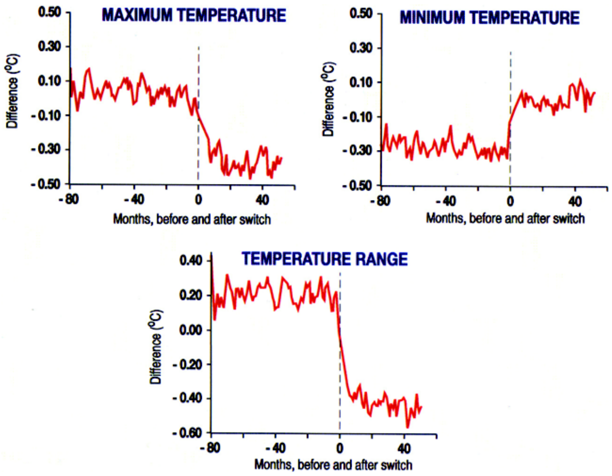

Fig. 1. The effect of changes in instrumentation from a liquid-in-glass thermometer housed in a wooden shelter to a thermistor housed in smaller plastic shelter in the Cooperative Observing Network in the United States. From Quayle et al. (1991).

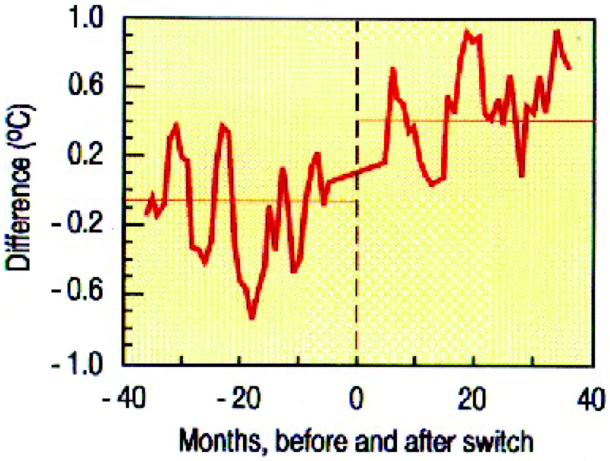

Fig. 2. Effects of changing instruments from the HO63 to the HO83 series on the maximum temperature in the United States (Karl et al. 1995).

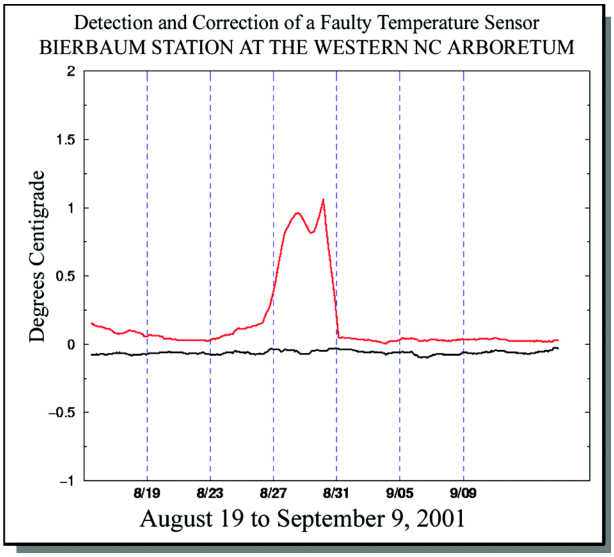

Fig. 3. Detection and correction of a temporary sensor drift at a Climate Reference Network station in western North Carolina. As there are three ventilated temperature thermistors at each site, cross checks among them, shown here between two pairs, enable a 1°C sensor drift at one of the sensors to be easily detected. In other networks these biases can go undetected and are difficult to correct.

location at a different time of day. Orbits tend to decay unless continually boosted, and the time of observations is apt to drift on sun-synchronous satellites (see Fig. 4). Instrumental calibration can be altered by the launch and by the space environment, and measurements may be affected by other instruments and the platform, requiring frequent calibration. All of these are issues for climate monitoring. For instance, changes in satellites and orbital decay have affected the cloud and radiation records (Stowe et al. 2002) and the satellite temperature record from the Microwave Sounder Unit (Hurrell and Trenberth 1998; Wentz and Schabel 1998). Adjusting for such changes has caused major problems in reanalyses (Santer et al. 1999; Trenberth et al. 2001). Hence for space-based platforms, climate monitoring requirements are more stringent than weather monitoring requirements. Nevertheless, upgrading to address climate requirements should be possible with incremental climate funds and a close working relationship between project and industrial engineers and scientists.

Satellites intended for monitoring should be launched into stable orbits that minimize the drift in time of the observation to less than 1 h over the lifetime of the satellite, or else boosters should be required to stabilize the orbit. Fortunately, the next generation of U.S. polar-orbiting satellites, the National Polar-Orbiting Environmental Satellite System (NPOESS), will include boosters to prevent satellite orbital drift, and recently NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) changed their orbital strategy: the *NOAA-16* polar orbiter has a targeted drift of no more than 30 min over a 5-yr lifetime, and succeeding polar satellites will have limited drift. A sufficient number of satellites should be operating to enable the diurnal cycle to be adequately sampled. Daily logs of satellite station keeping, calibration, and instrument status need to be routinely archived with the satellite observations to ensure the proper interpretation of the data. Satellites for monitoring should be launched prior the expected failure date of the operational satellite to ensure overlap of measurements that is essential for the climate record. This aspect has substantial cost implications. Not only does this affect the rate of satellite launches, but ground stations, processing centers, and data centers must be equipped to ingest and distribute the additional data. All instruments must be calibrated both prior to and post launch and an extensive ground truth validation should be sustained.

Ten Principles for Climate Data. A major effort is required to produce satisfactory climate data records from operational data. Over the past decade a number of basic principles have been developed for the delivery of long-term data with minimal space- and time-dependent biases. These principles were endorsed by the NRC, the United Nations Framework Convention on Climate Change, and in GCOS recommendations. Briefly described they include (NRC 1999) the following:

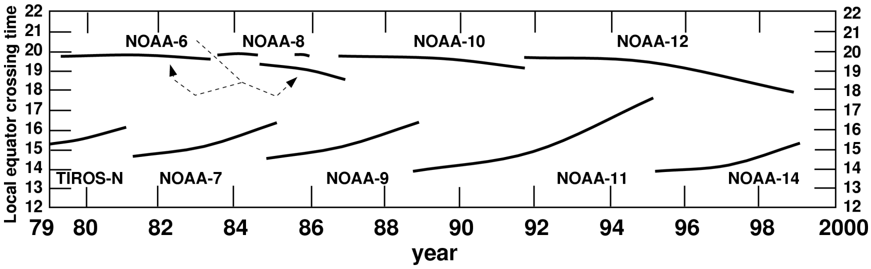

Fig. 4. The local equator crossing time of the ascending orbit of the operational NOAA series of satellites is given.

1) *Management of network change:* Assess how and the extent to which a proposed change could influence the existing and future climatology.
2) *Parallel testing:* Operate the old system simultaneously with the replacement system.
3) *Metadata:* Fully document each observing system and its operating procedures.
4) *Data quality and continuity:* Assess data quality and homogeneity as a part of routine operation procedures.
5) *Integrated environmental assessment:* Anticipate the use of data in the development of environmental assessments.
6) *Historical significance:* Maintain operation of observing systems that have provided homogeneous datasets over a period of many decades to a century or more.
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.
8) *Climate requirements:* Give network designers, operators, and instrument engineers climate monitoring requirements at the outset of network design.
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.

Research observations. Climate monitoring does not belie the need for other observations, particularly those oriented toward research to understand processes and improve models. Sustained and process observations are complementary and supplementary. However, the "technology transfer" of research observations to operational or sustained observations is not a trivial task. As principle 9 implies, the prototypical way to develop climate monitoring networks is to develop pilot-observing subsystems for research needs first. Once a research system is proven, then an operational system can be implemented. This was the procedure used to develop the Tropical Atmosphere Ocean (TAO) buoy array in the tropical Pacific for tracking El Niño, for example. Further discussion of the implementation of a sustained ocean observing system is given by Nowlin et al. (2001).

Scientific data stewardship. Effective data access is an extremely high priority (principle 10). Archive and access systems must be integrated into the real-time data processing system. A comprehensive scientific data stewardship program is required (Fig. 5) whereby the quality of observations and adequacy of performance of the observing system and analyses is assessed in near–real time for errors and missing data, and especially for detecting and correcting developing biases. Specialized teams best determine the latter. Feedback to observing system managers and operators is critical. Archived data often require calibration to produce reliable time series that represent the true nature of observed changes and variations. Reference datasets and model reanalyses are essential to obtain the highest-quality climate monitoring information. This includes data based on proxy paleoclimatic data, such as those used to construct a 1000-yr record of Northern Hemisphere temperatures (Mann et al. 1999) and more recent instrumental records. The veracity of the data can be tested through intercomparison and assessments to help determine whether a consistent picture of climate variability or change emerges. These kinds of analyses are required to ultimately produce climate quality products required to understand the observed climate record. Finally, appropriate efficient access to both model output and observational data must be provided. The scientific community knows that an absence of commitment to reliability and access leads to an archive that can neither deliver data when

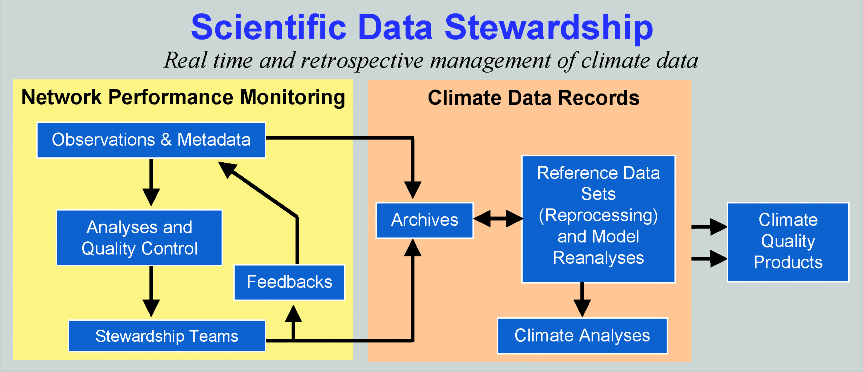

Fig. 5. A schematic depicting critical components needed for scientific data stewardship for climate.

needed, nor deliver the quality required. Data volume is expected to increase dramatically, creating challenges of preservation and effective access to the data.

At present, the combination of regional climate centers, national centers, and state climatologists cannot keep pace with the demand for climate information, so implementation of the scientific data stewardship and further development of climate extension services are both required.

LINKS TO CLIMATE MODELING AND PREDICTION. The monitoring program outlined above must be combined with analysis and generation of products, including the assimilation of the data into an operational climate model. Without this step there is neither adequate feedback to the monitoring program nor expert information on the data for the climate services.

Data assimilation and reanalysis. The synthesis of the observations through data assimilation using sophisticated models has proven to be an extremely effective tool for climate monitoring and analyses. Model-based data assimilation can incorporate all kinds of data and information, including space-based radiances and ground-based observations, and can be applied to other parts of the climate system in addition to the atmosphere. The models provide a consistent dynamical framework that helps enormously with quality control. Moreover, models can help ensure that measurements are made in the right places with the right frequency. Analyzed model-based fields, as well as long-term simulations of climate from models, are a valuable guide in the development and modification of climate observing systems. The models can be used to test and design an optimal mix of observations of different variables and sites, given the resources available, and with certain assumptions. While results have to be tempered with how well the model simulates the climate, this approach can be useful in designing the observing system.

There are major research challenges remaining to fully exploit the very different kinds of information from the various observing systems in data assimilation and reanalyses. In practice, four-dimensional data assimilation proves difficult because the information is spotty (single level, single profile), the error characteristics and covariances of the field may not be adequately known, and computational restrictions exist. The covariances are needed to be able to extend the influence of a single observation to its vicinity, perhaps tuned to particular situations, such as the state of El Niño–Southern Oscillation. A substantial research effort is required to capitalize on new observations, especially those from space. Plans with varying degrees of maturity are under way (for instance at the European Centre for Medium-Range Weather Forecasts; A. Hollingsworth 2001, personal communication) to include (i) ocean data assimilation of not only surface waves and physical variables, but also those involved in biogeochemistry (especially related to ocean color); (ii) the carbon cycle, including total column amounts of carbon dioxide; (iii) the land–biosphere, including soil moisture, radiative properties, hydrology and carbon stocks and fluxes; (iv) ozone, and other reactive gases as part of atmospheric chemistry and air quality; and (v) aerosol information. This approach is able to provide the best synthesis of all available data, including the merging of space-based and in situ observations.

The recent effort by NOAA and the National Aeronautics and Space Administration (NASA) to support a Joint Center for Satellite Data Assimilation is an important first step toward addressing many of these issues and in reanalyzing past data. Through reanalysis it is possible to obtain fields of information derived with consistent model physics, thus, eliminating biases in the climate record attributed to model changes. However, substantial research is needed on how to avoid the emergence of spurious changes given the changing mix of observations over time. Even omitting satellite observations does not address this problem, as the quality of radiosondes and their locations have continually evolved and will continue to do so.

Attribution and initial state for operational climate prediction. Attribution relates the observed climate change to causes, using a physically based model. There is a need to diversify this and assess how observed climate anomalies have arisen. Climate anomalies evolve from the previous state some time earlier, influenced by anomalous climate forcings in ways that may be only partially predictable. However, it is essential to be able to diagnose and assess in near–real time the relationships between the observed state and the forcings. This includes assessing the role of the inertia in the system from such things as soil moisture and heat content anomalies in the ocean or sea ice. Such assessments build the basis for confidence in predictions.

There is a need for much more than "what if" scenario-driven projections of future climate, such as those produced by the IPCC. Climate predictions as an initial value problem are crucial. Forecasts are needed of not just average conditions over a given place and time interval, but also the variability and extremes. These demands have implications for climate observations as well as modeling, and for climate research. In addition to tracking climate changes as they happen and providing information based upon resulting analyses, the observations are vital to establish the state of the climate system at any time. This is required for prediction purposes and is often referred to as the "initial state."

For weather prediction, detailed analyses of the atmosphere are required but uncertainties in the initial state grow rapidly over several days. For climate predictions, the initial state of the atmosphere is less critical; states separated by a day or so can be substituted. However, the initial states of other climate system components, some of which may not be critical to day-to-day weather prediction, become vital. For predictions of a season to a year or so, the sea surface temperatures, sea ice extent and upper ocean heat content, soil moisture, snow cover, and state of surface vegetation over land are all important (e.g., NRC 1994). Such initial value predictions are already operational for forecasting El Niño, and extensions to the global oceans are under way. On longer timescales, increased information throughout the ocean is essential. The mass, extent, thickness, and state of sea ice and snow cover are vital at high latitudes. The states of soil moisture and surface vegetation are especially important in understanding and predicting warm season precipitation and temperature anomalies (Schwartz and Karl 1990; Karl 1986) along with other aspects of the land surface. Any information on systematic changes to the atmosphere (especially its composition and influences from volcanic eruptions) as well as external forcings, such as from changes in the sun, is also needed.

Uncertainties in the initial state and the lack of detailed predictability of the atmosphere and other aspects of climate mandate that ensembles of predictions must be made and statistical forecasts given. Because of the buildup in greenhouse gases and other changes in atmospheric composition (IPCC 2001), the climate system is not in equilibrium and the oceans are evidently already slowly responding to the radiative imbalance at the top of the atmosphere (e.g., Levitus et al. 2001). Hence changes already mandated by recent forcings should add a predictable component to the climate system. Moreover, the long life of many greenhouse gases means that atmospheric concentrations are determined by the accumulation of past emissions. For the near future, the composition of the atmosphere is well determined by its present state plus current emission levels. Only after several decades do differences in emissions scenarios accumulate enough to matter. While the predictability from the initial state and decadal variability in the oceans is not yet adequately quantified, we would not be surprised to find that predictability extends to 50 years into the future when all of these factors are combined. Beyond this time horizon the IPCC approach that capitalizes only on the forcings is more appropriate as uncertainties in forcing scenarios overwhelm predictability arising from initial conditions.

INFRASTRUCTURE AND COMMITMENT.

The National Weather Service (NWS) and its relationship to the WMO provides one model for the components of a complete climate service. Elements include the observing system, the telecommunications system, the global data processing system, and the product dissemination system. A fundamental ingredient is the recognition of the global nature of the problem and the essential close international integration whereby data are freely and openly exchanged. The necessarily highly distributed observations around the world are funneled to national, then regional, and then to world meteorological centers, which produce the high-level analyses, develop products and forecasts, and disseminate these to the data producers and users. Other organizational elements of NOAA (such as NESDIS) support this model.

However, this not an ideal model for the required infrastructure needed to ensure the integrity and continuity of the climate observations. A commitment to maintaining systematic, objective continuous observations requires a good relationship between those who make observations and those who use them through reinforcement of the quid pro quo, that is not as apparent as it once was within WMO, so that those who produce observations fully benefit from the products. In addition there must be strong integral links to research and development in order to build and continuously improve the system.

We believe that the highest priority is to establish the infrastructure to ensure adequacy for operational climate monitoring and prediction, building on the NWS–WMO partnership. In addition to acquiring new observations, essential infrastructure has to be established to ensure the integrity and continuity of the observations, their analysis into products, assessment of why climate anomalies have arisen, and links to modeling and research activities. In particular, there is a fundamental need for a clear delineated responsibility for oversight of the health of an integrated observing system and resources to build and sustain a climate observing system operating under the 10 guideline principles. Such a responsibility should include a line of products for use in all aspects of climate, and an effective scientific data stewardship program (see the sidebar for a list of the responsibilities involved).

Some important operating principles include the following:

1) *Adequate support should be available for changes to instrumentation* in the context of maintaining a long-term climate record.
2) *Stable support* is an essential requirement for a climate observing system. Since this is to be a sustained activity, inflationary increases should be programmed into budget requests, rather than relying on budget initiatives.
3) *Contingency plans* should be made for resource shortfalls so that the operation of the system is not compromised.
4) Observing system activities should be regularly *reviewed.*
5) Activities should produce *annual plans* documenting accomplishments, future activities, and projected spending to ensure accountability.
6) Operating cost increases or other factors often require *flexibility and adjustments by the system operators* to maintain data flow while long-term solutions are sought. In making such adjustments, priorities, from highest to lowest, should be:
    (i) Data collection and archiving;
    (ii) Distribution of the raw data in near–real time;
    (iii) Quality control of the data in delayed mode and archiving of datasets;
    (iv) Development and maintenance of data access tools (e.g., Web sites);
    (v) Follow-on processing to produce analyses and reanalyses.

CONCLUSIONS. At the present time we do not have an adequate climate observing system. Instead we make do with an eclectic mix of observations mostly taken for other purposes. It would be impractical to develop an independent set of climate observations. However, there is a great need for new observations, in particular in the oceans—exciting research plans are underway to populate the oceans

RESPONSIBILITIES FOR OVERSIGHT

The United States should establish a unified and clear line of responsibility for the following areas in order to properly oversee the health of the climate observing system:

- **The development of improved networks to adequately sample, both spatially and temporally, critical climate state and forcing variables.**
- **Implementation of the 10 climate monitoring principles outlined by NRC and development of the required management guidelines.**
- **Continuing assessment of the health of the observing system, including near-real-time observing system performance for NOAA, the United States, and international observations; indeed, oversight of all observations made for climate.**
- **Funds for remedial actions to maintain the integrity of the observations, redress deficiencies, correct problems, and ensure continuity.**
- **Ensuring that all observations are utilized in real time and operational products are developed to help in the assessment and quality control, thus ensuring that at least one user funds the observations and associated system links.**
- **Free and open access and exchange of data.**
- **Interactions with other users and uses of the data, especially four-dimensional data assimilation, modeling, and prediction.**
- **Generation of initial fields from the assimilation to be used for model-based ensemble predictions as an initial value forecast on timescales from seasonal to several years to several decades (say out to 50 years).**
- **Analysis, diagnosis, and dissemination of model results to users. Facilitate access to the data and products; archive and ensure stewardship of the data.**
- **Continual dialogue between those who make observations and those who use them concerning the utility, quality, and problems with observations, in order to foster and encourage their continuation.**
- **Ability to adapt and evolve the system as new technologies become available, lower costs become possible, and new variables are needed.**
- **Ongoing reprocessing and reanalysis of data.**
- **Links to research.**
- **Advice from experts outside the process of operating the observing systems.**
- **Representation of the United States in international planning and agreements.**

Parts of this system are in place, but it is all needed to ensure that the data and information necessary to adequately monitor climate will be delivered.

with profiling floats. At the same time it is important that the observations be fully exploited and synthesized. We can create an exceptionally valuable, multipurpose resource by applying climate monitoring principles to observations taken for other purposes; adding new or enhanced observations; analyzing observations into products; creating an oversight facility to monitor and rectify problems in the system itself; and increasing focus on the climate needs related to management, access, and archival of the data that would provide an exceptionally valuable resource useful for multiple purposes. In particular, such a system can address all the needs that emerge when the climate is changing and past records may no longer be good guides to the future. Such an information base is essential and certain to be extremely cost effective in terms of the benefits it would render to society.

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