Recommendations

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RECOMMENDATIONS

This Chapter discusses steps needed to improve national capabilities in climate analysis, reanalysis, and attribution in order to better address key issues in climate science and to increase the value of this information for applications and decision making. Limitations, gaps in current capabilities, and opportunities for improvement that have been identified in earlier chapters, together with several related studies and reports, provide the primary foundations for the findings and recommendations provided here. The overarching goal is to provide high-level recommendations to improve national capabilities in climate analyses, reanalyses, and attribution in order to increase their value for scientific and practical applications.

4.1 NEED FOR A SYSTEMATIC APPROACH TO CLIMATE ANALYSIS AND REANALYSIS

As discussed throughout this report, reanalysis products have played a major role in advancing climate science and have supported numerous applications, including: monitoring climate and comparing current conditions with those of the past; providing initial conditions required for climate model predictions; supporting research on climate variability and change; enabling more reliable climate attribution; and providing benchmarks for evaluating climate models. Climate analyses and reanalyses are also being used in an increasing range of practical applications in sectors such as energy, agriculture, water resources, and insurance (*e.g.,* Schwartz and George, 1998; Pryor *et al.*, 2006; Challinor *et al.*, 2005; Pulwarty, 2003; Pinto *et al.*, 2007).

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These are important benefits. However, there are limitations in climate analysis and reanalysis products that presently constrain their value. Perhaps the largest constraint for climate applications is that, while the model and data assimilation system remain the same over the reanalysis period, the observing system does not, and this can lead to false trends, jumps, and other uncertainties in climate records (Arkin *et al.*, 2004; Simmons *et al.*, 2006; Bengtsson *et al.*, 2007).

Another constraint is the limited length of present reanalysis records, which now extend back to 1948, at most. Extending reanalysis back over a century or longer would improve descriptions and attribution of causes of important climate variations, such as the pronounced warm interval in the 1930s and 1940s, the Dust Bowl drought over much of the United States in the 1930s, and multi-decadal climate variations. International efforts such as the Global Climate Observing System (GCOS, 2004) and Global Earth Observation Systems of Systems (GEOSS, 2005) have identified the need for reanalysis datasets extending as far back as possible in order to compare recent and projected climate changes with those of the past.

The development of current climate analysis and reanalysis activities, while encouraging and beneficial, is occurring without clear coordination at national interagency levels, which may result in less than optimal progress and the inability to ensure a focus on problems of greatest scientific and public interest. Currently, no U.S. agency is charged with primary responsibility to ensure that the Nation has an ongoing capability in climate analysis or reanalysis, putting the sustainability of national capabilities at some risk.

The following recommendations focus on the value, needs, and opportunities for climate analysis and reanalysis in providing consistent descriptions and attribution of past climate variability and change, and in supporting applications and decision making at relevant national, regional and local levels. The recommendations point to the necessity for improved coordination between U.S. agencies and with international partners to develop an ongoing climate analysis and systematic reanalysis capacity that would address an increasing range of scientific and practical needs.

4.2 RECOMMENDATIONS FOR IMPROVING FUTURE CLIMATE ANALYSES AND REANALYSES

- **To better detect changes in the climate system, improve the quality and consistency of the observational data and reduce effects of observing system changes.**

As discussed in this Product, changes in observing systems (for example, the advent of comprehensive satellite coverage in the late 1970s), create significant uncertainties in the detection of true climate variations and trends over multiple decades. To reduce these uncertainties, closer collaborations are needed between observational and reanalysis communities to improve the existing global database of Earth system observations (Schubert *et al.*, 2006). Priorities include improving quality control, identification and correction of observational bias and other errors, the merging of various datasets, data recovery, improving the handling of metadata (that is, information describing how, when, and by whom a particular set of data was collected, content and structure of records, and their management through time), and developing and testing techniques to more effectively adjust to changes in observing systems (Dee, 2005).

This recommendation resonates with recommendations from other reports, including CCSP Synthesis and Assessment Product 1.1, which focuses on steps for understanding and reconciling differences in temperature trends in the lower atmosphere (CCSP, 2006). That report stated:

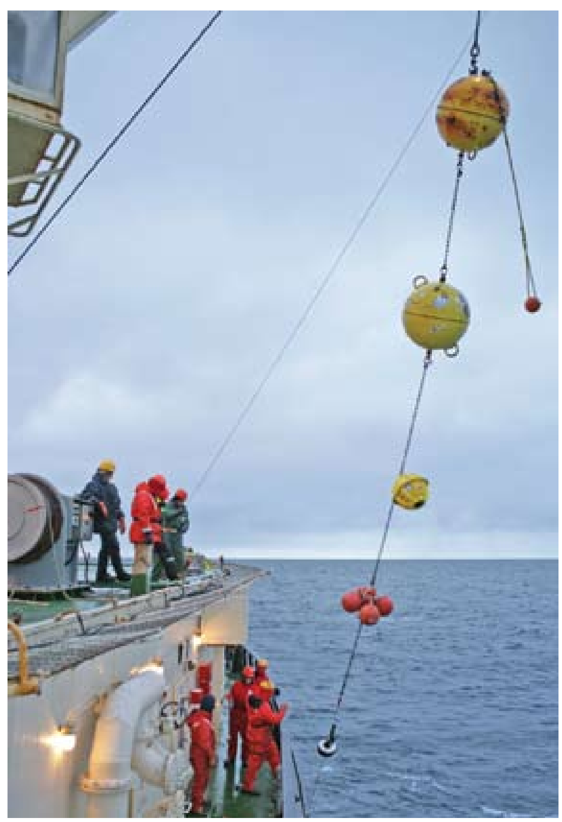
> Consistent with Key Action 24 of GCOS (2004) and a 10 Year Climate Target of GEOSS (2005), efforts should be made to create several homogeneous atmospheric reanalyses. Particular care needs to be taken to identify and homogenize critical input climate data, and to more effectively manage large-scale changes in the global observing system to avoid non-climatic influences (CCSP, 2006).

Recent World Meteorological Organization (WMO) reports emphasize the need for ongoing climate analyses and periodic reanalyses as critical parts of the Global Climate Observing System (GCOS) , *e.g.*, GCOS (2003, 2004), Simmons *et al.* (2006), Trenberth *et al.* (2006). GCOS (2004) states that “Parties are urged to give high priority to establishing a sustained capacity for global climate reanalysis, and to develop improved methods for such reanalysis, and to ensure coordination and collaboration among Centers in conducting reanalyses”.

Data quality control and expanding the use of available observations will be crucial to this effort. Significant gains are possible for both satellite and conventional observations (Arkin *et al.*, 2004). More research is required to understand biases in individual satellite data collections, to account for different resolutions and sensor measurements, and to minimize the impact of transitions between satellite missions, which may lead to data gaps or to apparent discontinuities if the satellite measurements are not cross-calibrated, *e.g.*, by comparing measurements obtained over an overlapping time period for the missions. In addition, early satellite data from the late 1960s and 1970s need further quality control and processing before they can be used effectively in reanalyses. Dedicated efforts are required to determine the full effects of changes in the observing systems, to focus on bias-corrected observations, and to assess remaining uncertainties in trends and estimates of variability. Observing System Experiments (OSEs) that consider the effects of inclusion or removal of particular data can be helpful in identifying and reducing possible harmful impacts of changes in observing systems.

- **Develop analysis methods that are optimized for climate research and applications. These methods should include uncertainty estimates for all reanalysis products.**

As discussed in Chapter 2, data assimilation techniques used in initial climate reanalyses were developed from methods optimized for use in numerical weather prediction. The primary goal of numerical weather prediction is to produce the best forecast. True four-dimensional data assimilation methods (using data that includes observations from before and after the analysis time, which is the start time of the forecast) have been developed for numerical weather prediction. However, the requirements for weather forecasts to be ready within a short time frame (typically within a few hours after the analysis time) result in observational data obtained after the beginning of the forecast cycle either not being assimilated at all or treated differently from observations obtained before or at the analysis time. The strong constraints placed by the needs for timely forecasts also substantially limit the capability of analyses to use the full historical observational database, which may not be collected until long after the forecast is completed.



These constraints are not relevant for

climate analyses, and modification of current data assimilation methods is needed to improve representations of long-term trends and variability (Arkin *et al.*, 2004). Further, many potentially available observations, including numerous satellite, surface temperature, and precipitation observations, could not be effectively assimilated within the first atmospheric reanalyses due to limitations of the models and assimilation techniques, and because some data were not available when the reanalyses were conducted (Kalnay *et al.*, 1996). Advances in data assimilation that have occurred since the pioneering reanalysis projects enable better and more complete use of these additional observations.

There are many applications of reanalyses, and it is likely that different scientific approaches will be required to optimally address particular problems.

To produce reanalyses that better serve climate research and applications, it will be essential to develop methods to more effectively use the wealth of information provided by diverse Earth observations, reduce the sensitivity of the data assimilation to changes in the observing system, and provide estimates of remaining uncertainties in reanalysis products. A major emphasis for efforts should be on the modern satellite era, essentially 1979 to present, during which time the number and diversity of observational data have expanded greatly but have yet to be fully utilized. An important development that should help to achieve this goal is the national Earth System Modeling Framework (ESMF, <http://www.esmf.ucar.edu>). The ESMF is a collaborative effort between NASA, NOAA, the National Science Foundation, and the Department of Energy that is developing the overall organization, infrastructure, and low-level utilities required to allow the interchange of models, model sub-components, and analysis systems. ESMF should greatly expand the ability of scientists outside the main data assimilation centers (*e.g.*, in universities and other organizations) to accelerate progress in addressing key challenges toward improving the analyses.

There are many applications of reanalyses, and it is likely that different scientific approaches will be required to optimally address particular problems. For example, if the primary goal is to optimize the detection of climate trends, particular care must be given to minimizing effects of changing observing systems so as to ensure the highest quality analysis over an extended time period. In this case, an appropriate reanalysis strategy may be to use a subset of very high quality data that is available continuously, or nearly continuously, over as long a period as feasible. Conversely, if the primary goal is to perform detailed studies of processes at high space and time resolutions, the most accurate analysis at any given time may be preferred. Here, the best strategy may be to take advantage of all available observations. In any case, uncertainties in the analyses and their implications should be appropriately documented.

Alternative data assimilation methods should be explored for their potential benefits. One alternative that is being examined intensively, ensemble data assimilation, shows considerable promise in addressing a wide range of problems. This technique uses multiple model predictions (called an "ensemble") to estimate where errors may be particularly large or small at a given time. This time- and location-dependent uncertainty information is then incorporated into the analysis (Houtekamer and Mitchell, 1998; Whitaker and Hamill, 2002). This approach provides estimates of uncertainties in the full range of reanalysis products (including, for example, the components of the water cycle). Ensemble data assimilation is becoming more economical with the development of innovative methods to take advantage of massively parallel computing (Ott *et al.*, 2004). In addition, ensemble-based approaches are being developed that explicitly account for model error (Zupanski and Zupanski, 2006), thereby providing a potentially important step toward better estimating analysis uncertainties.

- **To improve the description and understanding of major climate variations that occurred prior to the mid-twentieth century, develop the longest possible consistent record of past climate conditions.**

For many applications, the relatively short period encompassed by initial reanalyses is a very important constraint. Current reanalysis datasets extend back to the mid-twentieth century at most. As a consequence, many climate variations of great societal interest, such as the prolonged Dust Bowl drought of the 1930s, are not included in present reanalyses, increasing uncertainties in both their descriptions and causes.

Recent research has demonstrated that a reanalysis through the entire twentieth century, and perhaps earlier, is feasible using only surface pressure observations (Whitaker *et al*., 2004; Compo *et al*., 2006). Extending reanalysis back over a century or longer would be of great value in improving descriptions and attribution of causes of important climate variations such as the pronounced warm interval in the 1930s and 1940s, the Dust Bowl drought, and other multi-decadal climate variations. International efforts such as the GCOS and GEOSS have identified the need for reanalysis datasets extending as far back as possible to compare the patterns and magnitudes of recent and projected climate changes with past changes (GCOS, 2004; GEOSS, 2005). Such reanalysis datasets should also enable researchers to better address issues on the range of natural variability of weather and climate and increase understanding of how El Niño-Southern Oscillation and other climate patterns alter the behavior of extreme events.

Alternative assimilation methods should also be evaluated for obtaining maximum information for estimating climate variability and trends from very sparse observations and from surface observations alone, where observational records are available over much longer periods than other data sources. Ensemble data assimilation methods have already shown considerable promise in this area (Ott *et al*., 2004; Whitaker *et al*., 2004; Compo *et al*., 2006; Simmons *et al*., 2006), and, as mentioned previously, also provide estimates of analysis uncertainty. Improved methods of estimating and correcting observational and model errors, recovery of historical observations, and the development of optimal, consistent observational datasets will also be required in this effort.

- **To improve decision support, produce future climate reanalysis products at finer space scales (*e.g.*, resolutions of 10 miles rather than 100 miles) and emphasize products that are most relevant for applications, such as surface temperatures, winds, cloudiness, and precipitation.**

For many applications, the value of the initial reanalysis products has been constrained by their relatively coarse horizontal resolution (200 kilometers or approximately 120 miles). For many users, improved representation of the water cycle (inputs, storage, outputs) is a key need. In addition, land-surface processes are important for both surface energy (temperature) and water balance, with land cover and land use becoming increasingly important at smaller scales. These processes should be research focus areas for future improvements.

Within the United States, one step forward in addressing these issues is the implementation of NASA's new reanalysis project (MERRA, see Box 2.2 for a detailed description), which will provide global reanalyses at approximately 50-kilometer (about 30-mile) resolution and has a focus on providing improved estimates of the water cycle <http://gmao.gsfc.nasa.gov/research/merra/>. Another important step forward is the completion of the North American Regional Reanalysis, or NARR (Mesinger *et al*., 2006). While this is a regional analysis for North America and adjacent areas, rather than global reanalysis, it is at considerably higher resolution than the global reanalyses with a grid spacing of 32 kilometers (about 20 miles). Importantly, NARR also incorporates significant advances in modeling and data assimilation that were made following the initial global reanalysis by NOAA and the National Center for Atmospheric Research (Kalnay *et al*., 1996), including the ability to assimilate precipitation observations. This has resulted in substantial improvements in precipitation analyses over the contiguous United States as well as improvements in near-surface temperatures and wind fields (Mesinger *et al*., 2006). While advances are impressive, early studies show that further improvements are

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needed to accurately represent the complete water cycle (*e.g.*, Nigam and Ruiz-Barradas, 2006). The ability to improve analyses of key surface variables and the water cycle therefore remain as important challenges.

Future climate analyses and reanalyses should incorporate additional climate system components that are relevant for decision making and policy development, for example, a carbon cycle to aid in identifying changes in carbon emissions sources and removal processes.

- **Develop new national capabilities in analysis and reanalysis that focus on variables that are of high relevance to policy and decision support. Such variables include those required to monitor changes in the carbon cycle and to understand interactions among Earth system components (atmosphere, ocean, land, cryosphere, and biosphere) that may lead to accelerated or diminished rates of climate change.**

Initial reanalyses focused on reconstructing past atmospheric conditions. For both scientific and practical purposes, there is a strong need to consider other Earth system components, such as the ocean, land, cryosphere, and biosphere, as well as variables that are of interest for climate but are of less immediate relevance for weather prediction (*e.g.*, related to the carbon cycle). As discussed in Chapter 2, such efforts are ongoing for ocean and land data assimilation but are still in relatively early stages. The long-term goal should be to move toward ongoing analyses and periodic reanalyses of major Earth system components relevant to climate variability and change.

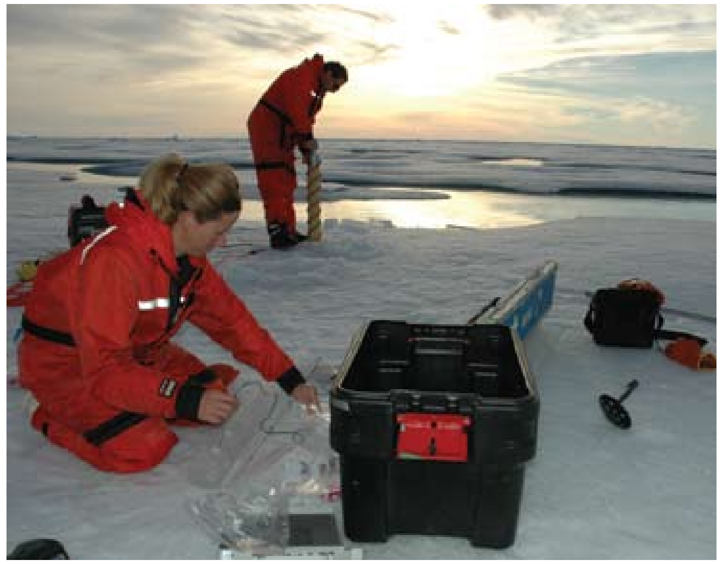
Future climate analyses and reanalyses should incorporate additional climate system components that are relevant for decision making and policy development, for example, a carbon cycle to aid in identifying changes in carbon emissions sources and removal processes. A reanalysis of the chemical state of the atmosphere would improve monitoring and understanding of air quality in a changing climate, aerosol-climate interactions, and other key policy-relevant issues. Initial attempts at coupling of climate system components, *e.g.*, ocean-atmosphere reanalysis, should be fostered, with a long-term goal being to develop an integrated Earth system analysis (IESA) capability that includes interactions among the Earth system components (atmosphere, ocean, land, snow and ice, and biological systems).

An IESA would provide the scientific community, resource managers, decision makers, and policy makers with a high quality, internally consistent, continuous record of the Earth system that can be used to identify, monitor, and assess changes in the system over time. Developing an IESA would also contribute to improved descriptions and understanding of the coupled processes that may produce rapid or accelerated climate changes, for example, from high-latitude feedbacks related to changes in sea ice or melting of permafrost that may amplify an initial warming due to natural or anthropogenic causes. Key processes include: atmosphere-ocean interactions for physical and biogeochemical processes; climate feedbacks from snow and ice processes; carbon cycle feedbacks; and atmosphere-land-biosphere interactions.

To achieve an IESA will require a sustained capacity to assimilate current and planned future observations from diverse platforms into Earth system models. This approach will be essential for realizing the full value of investments in current and proposed future observing systems within GEOSS, as it provides the means of integrating diverse datasets together to obtain a unified, physically consistent description of the Earth system. It would also take advantage of rapid advances in Earth system modeling, while providing the ability to evaluate models used for attribution and climate predictions and projections.

Recent efforts have shown the feasibility of extending initial atmospheric analyses beyond traditional weather variables. For example, the European Union has funded a project, the Global Environment Monitoring System (GEMS), that is incorporating satellite and *in situ* data (data collected at its original location) to develop an analysis and forecast capability for atmospheric aerosols, greenhouse gases, and reactive gases (Hollingsworth *et al.*, 2005). The GEMS operational system will be an extension of current weather data assimilation capabilities, with implementation planned for 2009. The main users of the GEMS Project are intended to be policy-makers, operational regional air quality and environmental forecasters, and the scientific community. GEMS will support operational regional air-quality and "chemical weather" forecast systems across Europe. Part of the motivation for this project is to provide improved alerts for events such as the 2003 heat waves in Western Europe that led to at least 22,000 deaths, mostly due to heat stress, but also connected to poor air quality (Kosatsky, 2005). GEMS will generate a reanalysis of atmospheric dynamics and composition, and state-of-the-art estimates of the emissions sources and removal processes as well as how gases and aerosols are transported across continents. These estimates are designed to meet key information requirements of policy-makers, and to be relevant to the Kyoto and Montreal Protocols and the United Nation Convention on long-range trans-boundary air pollution (Hollingsworth *et al.*, 2005).

Within the United States, NOAA has developed plans to use a fully coupled atmosphere-land-ocean-sea ice model for its next generation of global reanalysis, extending over the period 1979 to 2008 (S. Saha, personal communication, 2007). This reanalysis is based on the NOAA-NCEP Climate Forecast System (CFS) model (Saha *et al.*, 2006). While the component analyses will be performed separately through independent atmosphere, land, ocean, and sea ice data assimilation systems, the use of a coupled model provides consistent initial estimates for all variables that is an important step toward a fully coupled Earth system analysis. Current plans are to begin production and evaluation of this reanalysis in 2008. This global atmosphere-ocean reanalysis would provide important advances on a number of fronts, taking advantage of improvements in modeling, data assimilation, and computing that have occurred since the pioneering NCEP-NCAR reanalysis. Atmospheric resolution will also be greatly increased, from approximately 200 kilometers (120 miles) in the earlier version to 30 to 40 kilometers (around 20 to 25 miles) in the new version. In addition to atmospheric, ocean, and land data assimilation, significant new efforts are examining the use of data as-



similation techniques to analyze other aspects of the Earth system, with one important focus being to better represent and identify gas and aerosol emissions sources and removal processes in the atmospheric carbon cycle (Peters *et al.*, 2005).

- **Develop a more coordinated, effective, and sustained national capability in analysis and reanalysis to support climate research and applications.**

Without a clear and systematic institutional commitment, future efforts in climate analysis and reanalysis are likely to be *ad hoc*, and are unlikely to result in high quality, sustained, cost-effective products. Developing a national capability in climate (and Earth system) analysis and reanalysis will be essential to achieving key CCSP objectives and, in particular, CCSP Goal 1: "Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of climate variability and change" (CCSP, 2003).

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This idea was first highlighted over 15 years ago in a National Research Council report (NRC, 1991) that outlined a strategy for a focused national program on data assimilation for the Earth system. A key recommendation of that report was that "A coordinated national program should be implemented and funded to develop consistent, long term assimilated datasets … for the study of climate and global change". This recommendation has been reiter-

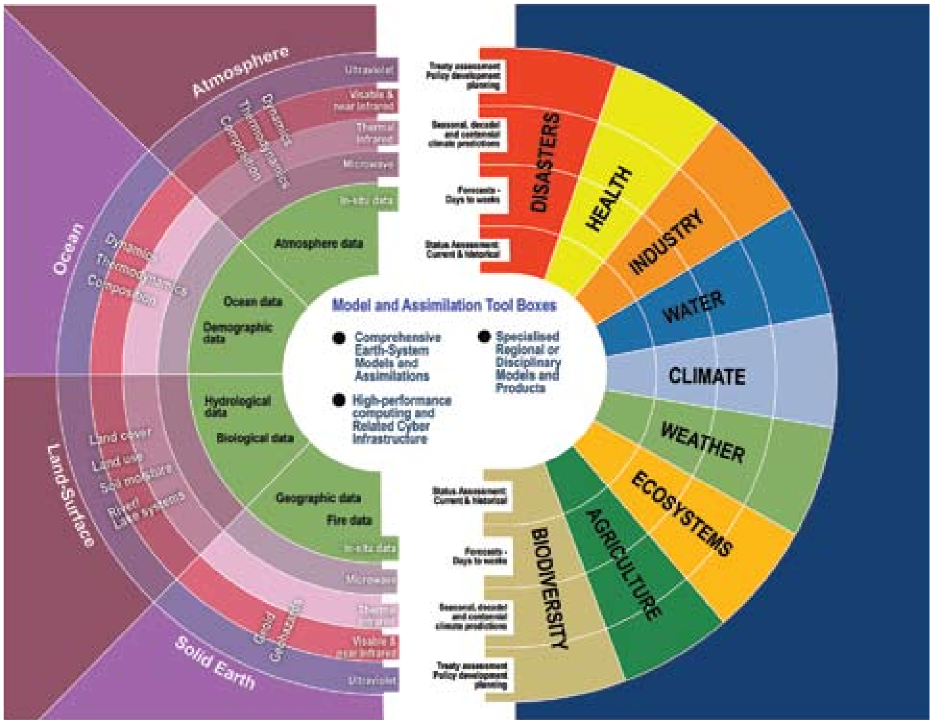


Figure 4.1 From Hollingsworth (2005), based on the GEOSS Implementation Plan (GEOSS, 2005), illustrating the transformation of observations into predictive and current-status information. On the right-hand side are products from an Earth system forecasting system and associated specialized models organized in GEOSS categories of socioeconomic benefits, stratified by the lead time required for products (current status assessments, forecast time-range, long-term studies of reanalysis). On the left-hand side are observational requirements for a comprehensive Earth system model, including *in situ* data as well as current and projected satellite data. In the center are "tool boxes" needed to achieve the transformation from observations into information.

ated frequently in several subsequent studies and reports; for example, in a recent interagency-sponsored workshop whose participants included scientists and managers from several federal agencies, the academic community, and international organizations (Arkin *et al.*, 2004). As discussed in Hollingsworth *et al.* (2005), such an activity is also essential to realizing the full benefits of GEOSS, because of its crucial role in transforming Earth system observations into the status-assessment and predictive products required by GEOSS across many areas of socioeconomic interest (Figure 4.1).

To be truly successful such a program must include multiple agencies, since it requires resources and expertise in a broad range of scientific disciplines and technologies beyond that of any single agency (*e.g.*, atmosphere, ocean, land surface and biology, observations and modeling, measurements, computing, data visualization and delivery). It also will need strong ties with the Earth science user community, to ensure that the analysis and reanalysis products satisfy the requirements of a broad spectrum of users and provide increasing value over time.

4.3 NEED FOR IMPROVED CLIMATE ATTRIBUTION

Recent events underscore the socioeconomic significance of credible and timely climate attribution. For instance, the recent extremely warm year of 2006 in the United States raises questions over whether the probability of occurrence of such warm years has changed, what the factors are contributing to the changes, and how such factors might alter future probabilities of similar or warmer years. Policy and decision makers want to know the answers to these questions because this information can be used within planning and response strategies. What climate processes are responsible for the persistent western U.S. drought and what implications does this have for the future? Planners are assessing the sustainability and capacity of the region for further growth, and the resilience of water resources to climate variations and change is an important factor that they must consider. What processes contributed to the extremely active 2004 and 2005 North Atlantic hurricane seasons as well as to the general increase in hurricane activity in this region since the mid-1990s? Emergency managers want to know the answers to such questions and related implications for the coming years, in order to better prepare for the future.

This Product has identified several outstanding challenges in attribution research that are motivated by observed North American climate variations that occurred during the reanalysis period but have yet to be fully explained. For instance, what is the cause of the so-called summertime "warming hole" over the central United States? The results of Chapter 3 indicate that this pattern is inconsistent with an expected anthropogenic warming obtained from coupled model simulations, although model simulations with specified sea surface temperature variations over the period are able to represent aspects of this pattern. Other forcings resulting from human activities, including by atmospheric aerosols and land use and land cover changes, may play significant roles but their effects have yet to be quantified. From a decision-making perspective, it is important to know whether the absence of summertime warming in the primary grain producing region of the United States is a natural climate variation that may be temporarily offsetting long-term human-induced warming, or whether current climate models contain specific errors that are leading to systematic overestimates of projected warming for this region.

As emphasized in Hegerl *et al.* (2006), to better serve societal interests there is a need to go beyond detecting and attributing the causes of global average surface temperature trends to consider the causes of other climate variations and changes. As detection and attribution studies move toward smaller scales of space and time and consider a broader range of variables, important challenges must be addressed.

4.4 RECOMMENDATIONS FOR IMPROVING CLIMATE ATTRIBUTION CAPABILITIES

- **Develop a national capability in climate attribution to provide regular and reliable explanations of evolving climate conditions relevant to decision making.**

Similar to the present status of U.S. efforts in climate analysis and reanalysis, attribution research is presently supported through a range of agency research programs without clear national coordination (Trenberth *et al.*, 2006). This may limit abilities to address attribution problems of highest scientific or public interest. There are also no clearly designated responsibilities to communicate state-of-science findings on attribution. Therefore, the public and media are often exposed to an array of opinions on causes for observed climate events, with diametrically opposed views sometimes expressed by different scientists from within the same agency. In many cases, these statements are made without any formal attribution studies, and in some cases subsequent attribution research has shown that public statements on probable causes are extremely unlikely (Hoerling *et al.*, 2007).

The ability to attribute observed climate variations and change provides an essential component within a comprehensive climate information system designed to serve a broad range of public needs (Trenberth *et al.*, 2006; NIDIS, 2007). Reliable attribution provides a scientific underpinning for improving climate predictions and climate change projections and information useful for evaluating policy options and responses and managing resources. This capability is also vital for assessing climate model performance and identifying where future model improvements are most needed. The associated scientific capacity should include providing coordination of and access to critical observational and reanalysis datasets as well as output from model experiments in which different forcings are systematically included or excluded. Without a clear and systematic institutional commitment, future efforts in climate attribution are likely to continue to be *ad hoc*, and unlikely to be conducted as efficiently and effectively as possible.

Reliable attribution provides a scientific underpinning for improving climate predictions and climate change projections and information useful for evaluating policy options and responses and managing resources.

In order to develop this capacity, there is a need to improve coordination of, and access to, climate model and observational data relevant for climate attribution. Compared with earlier climate change assessments, a major advance in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report was the much larger number of simulations obtained from a broader range of models (IPCC, 2007). Taken together with additional observations, these more extensive simulations helped provide for the first time quantitative estimates of the likelihoods of certain aspects of future climate change. This work was facilitated substantially through the Program for Climate Model Diagnosis and Intercomparison (PCMDI), which provided facilities for storing and distributing the very large datasets that were generated from the numerous climate model simulations of past climate and climate change projections that were generated for the IPCC report. Other basic infrastructure tasks provided through PCMDI included: the development of software for data management; visualization and computation; the assembly and organization of observational datasets for model validation; and consistent documentation of climate model features. Providing similar infrastructure support for a broader range of necessary model simulations will be vital to continuing advances in research on climate attribution. In addition to fundamental data management responsibilities, advances in scientific visualization and diagnostic and statistical methods for intercomparing and evaluating results from model simulations would substantially facilitate future research.

There is a need to improve coordination of, and access to, climate model and observational data relevant for climate attribution.

The continual interplay between observations and models for climate analysis and reanalysis that occurs in attribution studies is fundamental to achieving the long-term objectives of the CCSP (CCSP, 2003). Detection and attribution research provide a rigorous comparison between model-simulated and observed climate changes. Climate variations and changes that can be detected and attributed to factors external to the climate system, such as from solar variations, greenhouse gas increases produced by human activities, or aerosols ejected into the atmosphere from volcanic eruptions, help to constrain uncertainties in future predictions and projections of climate variations and change. Climate variations that can be attributed to factors that are internal to the climate system, such as sea surface temperature or soil moisture conditions, can also help constrain uncertainties in future predictions of climate variations over time periods of seasons to decades. At the same time, where there are significant discrepancies between model simulations and observations that are outside the range of natural climate variability, the information provided through detection and attribution studies helps identify model deficiencies and areas where additional effort will be required to reduce uncertainties in climate predictions and climate change projections.

- **Focus research to better explain causes of climate conditions at regional and local levels, including the roles of changes in land cover, land use, atmospheric aerosols, greenhouse gases, sea surface temperatures, and other factors that contribute to climate change.**

While significant advances have occurred over the past decade in attributing causes for observed climate variations and change, there remain important sources for uncertainties. These sources become increasingly important in going from global to regional and local scales. They include: uncertainties in observed magnitudes and distributions of forcing from various processes; uncertainties in responses to various forcings; uncertainties in natural variability in the climate system, that is, variability that would occur even in the absence of changes in external forcing.

To address these uncertainties, further research is needed to improve observational estimates of changes in radiative forcing factors over a reference time period, for example, the twentieth century to the present. In addition to greenhouse gas changes, such factors include variations in solar forcing, effects of atmospheric aerosols, and land use and land cover changes. The relative importance of these factors varies among climate variables, and space and time scales. For instance, land use changes are likely to have a relatively small effect in changing global average temperature (*e.g.*, Matthews *et al.*, 2004) but may have more substantial effects on local weather (*e.g.*, Pielke *et al.*, 1999; Chase *et al.*, 2000; Baidya and Avissar, 2002; Pielke, 2001). Aerosol variations are also likely to be increasingly important in forcing climate variations at regional to local levels (Kunkel *et al.*, 2006). Detection and attribution results are sensitive to forcing uncertainties, which can be seen when results from models are compared with different forcing assumptions (*e.g.*, Santer *et al.*, 1996; Hegerl *et al.*, 2000; Allen *et al.*, 2006).

More comprehensive and systematic investigations are also required of the climate response to individual forcing factors, as well as to combinations of factors. Parallel efforts are necessary to estimate the range of unforced natural variability and model climate drift. Ensemble model experiments should be performed with a diverse set of coupled climate models over a common reference period, such as the twentieth century to present, in which different factors are systematically included or excluded. For example, model simulations including and excluding changes in observed land cover are needed to better quantify the potential influence of anthropogenic land cover change, especially at regional or smaller levels. Extended control simulations are required with the same models to estimate natural internal variability and assess model climate drifts. The ability to carry out the extensive simulations that are required will depend strongly on the availability of high performance computing capabilities.

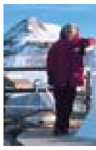
A first estimate of combined model errors and forcing uncertainties can be determined by combining data from simulations forced with different estimates of radiative forcings and simulated with different models (Hegerl *et al.*, 2006). Such multi-model fingerprints provide an increased level of confidence in attribution of observed warming from increases in greenhouse gases and cooling from sulfate aerosols (Gillett *et al.*, 2002). Both forcing and model uncertainties need to be explored more completely in order to better understand the effects of forcing and model uncertainty, and their representation in detection and attribution (Hasselmann, 1997). Because the use of a single model may lead to underestimates of the true uncertainty, it is important that such experiments reflect a diversity of responses as obtained from a broad range of models (Hegerl *et al.*, 2006).

As discussed in Chapter 3, atmospheric models forced by observed changes in sea-surface temperatures have shown considerable ability to reproduce aspects of climate variability and change over North America and surrounding regions since 1950. A growing body of evidence indicates that changes in the oceans are central to understanding the causes of other major climate anomalies. Additional assessments are required to better determine the atmospheric response to sea surface temperature variations and, in particular, the extent to which changing ocean conditions may account for past and ongoing climate variations and change. As part of this assessment, ensemble experiments should be conducted with atmospheric models forced by observed sea-surface temperatures over the same baseline time period and in parallel with the experiments recommended earlier.

More comprehensive and systematic investigations are required of the climate response to individual forcing factors, as well as to combinations of factors. Parallel efforts are necessary to estimate the range of unforced natural variability and model climate drift.

- **Explore a range of methods to better quantify and communicate findings from attribution research.**

There is a need to develop alternative approaches to more effectively communicate knowledge on the causes of observed climate variability and change, and potential implications for decision makers (*e.g.*, for risk assessment). New methods will become increasingly important in considering variability and changes at smaller space and time scales than in traditional global change studies, as well as for assessments of factors contributing to the likelihood of extreme weather and climate events. There is a strong need to go beyond present communication methods to approaches that include specific



responsibilities for addressing questions of public interest.

Much of the climate attribution research to date has focused on identifying the causes for long-term climate trends. An important new challenge is quantifying the impact of various factors that influence the probability of specific weather or short-term climate events (CCSP, 2008). An often-stated assertion is that it is impossible to attribute a single event in a chaotic system to external forcing, although it is through such events that society experiences many of the impacts of climate variability and change. As discussed in Hegerl *et al.* (2006), this statement is based in part on an underlying statistical model that assumes that what is observed at any time is a deterministic response to forcing upon which is superposed random "climate noise". From such a model, it is possible to estimate underlying deterministic changes in certain statistical properties, for example, expected changes in event frequency over time, but not to attribute causes for individual events themselves.

In order to be more responsive to questions from government, media, and the public, a coordinated, ongoing activity in climate attribution should include specific responsibilities for addressing questions of public and private interests on the causes of observed climate variations and change.

However, several recent studies demonstrate that quantitative probabilistic attribution statements are possible for individual weather and climate events, if the statements are framed in terms of the contribution of the external forcing to changes in the relative likelihood of occurrence of the event (Allen, 2003; Stone and Allen, 2005; Stott *et al.*, 2004). Changes in likelihood in response to a forcing can be stated in terms of the "fraction of attributable risk" (FAR) due to that forcing. The FAR has a long-established use in fields such as epidemiology, for example, in determining the contribution of a given risk factor (*e.g.*, tobacco smoking) to disease occurrence (*e.g.*, lung cancer). This approach has been applied to attribute a fraction of the probability of an extreme heat wave observed in Europe in 2003 to anthropogenic forcing (Stott *et al.*, 2004) and more recently, to the extreme annual U.S. warmth of 2006 (Hoerling *et al.*, 2007). These probabilistic attribution findings related to risk assessment should be explored further, as this information may be more readily interpretable and usable by many decision makers.

There is also a strong need to go beyond present limited efforts at communicating knowledge on the causes of observed climate variations and change. In order to be more responsive to questions from government, media, and the public, a coordinated, ongoing activity in climate attribution should include specific responsibilities for addressing questions of public and private interests on the causes of observed climate variations and change. This capability will form a necessary collaborative component within a national climate information system designed to meet the core CCSP objective of providing science-based information for improved decision support (CCSP, 2003).