Chapter 4. Recommendations

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SUMMARY OF MAJOR RECOMMENDATIONS

The following recommendations are aimed at improving the scientific and practical value of climate analyses and reanalyses.

1. Observational data set development for climate analysis and reanalysis should place high priority on improving the quality, homogeneity and consistency of the input data record to minimize potential impacts of observing system changes.

Toward this end, there should be a focused interagency effort that is coordinated with international partners to create a comprehensive, quality-controlled global database of conventional and satellite data suitable for climate analysis and reanalysis.

2. Future efforts should include a focus on developing data assimilation and analysis methods that are optimized for climate purposes, and on providing estimates of uncertainties in all reanalysis products.

It is 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.

3. One stream of reanalysis efforts should focus on producing the longest possible consistent record of surface, near surface, and upper-air variables for the study of global climate variability and change.

Toward this end, alternative assimilation methods should be evaluated for obtaining maximum information for estimating climate variability and trends from very sparse observations and using only surface observations, for which observational records are available over relatively long time periods (more than a century).

4. Another stream of research efforts should focus on producing climate reanalysis products at finer spatial resolution, with increasing emphasis on improving the quality of products that are of particular relevance for applications, *e.g.*, surface temperatures, winds and precipitation.

For many users, better representation of the water cycle is a key concern. Land surface processes are important for both surface energy (temperature) and water balance, with effects of changes in land cover and land use becoming increasingly important at smaller scales.

5. Increasing priority should be given to developing national capabilities in analysis and reanalysis beyond traditional weather variables, and to include effects of coupling among Earth system components.

Future climate analyses and reanalyses should incorporate additional atmospheric constituents that are of high relevance for decision making and policy development, for example, changes in greenhouse gases and aerosols, as well as effects of land cover and land use changes. There is a strong need to develop analysis and reanalysis capabilities for climate system components beyond the atmosphere, *e.g.*, ocean, land surface (including vegetation), and cryosphere. Initial attempts at coupling of climate system components (*e.g.*, coupled ocean-atmosphere reanalysis) should be fostered, with a long-term goal of developing an integrated Earth system analysis capability.

6. There is a specific and pressing need to go beyond present *ad hoc* project approaches to develop a more coordinated, effective, and sustained national capability in climate analysis and reanalysis.

Coordinating and developing a national capability in climate (and more broadly, Earth system) analysis and reanalysis will be essential to achieving key objectives across the Climate Change Science Program and, in particular, CCSP Goal 1: "Improve knowledge of the Earth's past and present climate and environment, including its natural variability…".

The following additional priorities are recommended for reducing uncertainties in climate attribution and increasing the value of this information for decision support.

7. A national capability in climate attribution should be developed to provide a foundation for regular and reliable explanations of evolving climate conditions relevant to decision making. This will require advances in Earth system modeling, analysis and reanalysis.

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.

8. An important focus for future attribution research should be to develop capabilities to better explain causes of climate conditions at regional to local scales, including the roles of changes in land cover/use and aerosols, greenhouse gases, sea surface temperatures, and other forcing factors.

The coordination of research on attributing causes for regional to local climate variations and change will be essential to achieving key objectives across the U.S. Climate Change Science Program, and in particular, CCSP Goal 1 to "… improve understanding of the causes of climate variability and change".

9. A range of methods should be explored 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, as well as potential implications for decision makers (*e.g.*, changes related to probabilistic 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 probabilistic assessments of factors contributing to the relative likelihood of extreme weather and climate events. There is strong need to go beyond present *ad hoc* communication methods to more coordinated approaches that include specific responsibilities for addressing questions of public interest.

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 such products for applications and decision making. Limitations, gaps in current capabilities and opportunities for improvement identified in previous 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 that are aimed at improving the scientific and practical value of future climate analyses and reanalyses, as well as national capabilities in climate attribution.

4.1 ON THE NEED FOR A SYSTEMATIC APPROACH TO CLIMATE ANALYSIS AND REANALYSIS

As discussed throughout this report, the first generation of reanalysis products has played a major role in advancing climate science and supported numerous applications. Some of the scientific applications include serving as a baseline dataset for climate monitoring, providing initial conditions for climate simulations and predictions, enabling research on climate variability and change, strengthening the basis for climate attribution, and providing a benchmark for evaluating climate models. Climate analyses and reanalyses are being used in an increasing range of practical applications as well, in sectors such as energy, agriculture, water resource management and planning, insurance and reinsurance (Pulwarty, 2003; Adger *et al.*, 2007, Chapter 17).

Despite these important benefits, current climate analysis and reanalysis products also have significant shortcomings that constrain their value. Perhaps the most serious shortcoming for climate applications is that, while the model and data assimilation system remains fixed over the reanalysis period, the observing system does not, and this can lead to apparent changes in perceived climate (*e.g.*, Arkin *et al.*, 2004; Simmons *et al.*, 2006; Bengtsson *et al.*, 2007).

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 multi-decadal climate variations. International efforts such as the Global Climate Observing System, or GCOS (GCOS, 2004) and Global Earth Observation Systems of Systems (GEOSS, 2005) 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.

The development of current climate analysis and reanalysis activities, while encouraging and beneficial, appears to be occurring without clear coordination of efforts at national interagency levels, which may result in sub-optimal progress and an inability to ensure a focus on problems of greatest scientific and public interest. At present, no agency is charged with responsibility for ensuring that the nation has an ongoing capability in climate analysis or reanalysis, putting at some risk the sustainability of national capabilities in this area.

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 scales. They point to the need for improved coordination across agencies and with international partners to develop an ongoing climate analysis and systematic reanalysis capacity, as well as advances required in climate science to support more useful products.

4.2 RECOMMENDATIONS FOR IMPROVING FUTURE CLIMATE ANALYSES AND REANALYSES

As discussed throughout this report, changes in observing systems during the period, for example, comparing times prior to and following the major changes associated with the advent of comprehensive satellite coverage in the late 1970s, create significant uncertainties in the detection of true multi-decadal variations and trends. These findings motivate our first recommendation.

1. Observational data set development for climate analysis and reanalysis should place high priority on improving the quality, homogeneity and consistency of the input data record to minimize potential impacts of observing system changes.

Toward this end, there is a strong need to increase the collaboration 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 data sets, data recovery, improved handling of metadata, and developing and testing adaptive bias-correction techniques (Dee, 2005) to more effectively adjust to a changing observing system.

Recommendation 1 resonates with recommendations from other reports, including the recently completed CCSP Report focusing on steps for understanding and reconciling differences in temperature trends in the lower atmosphere (Karl *et al.*, 2006: CCSP SAP1.1). 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 1.1 Recommendation 4, p. 124)

The needs for ongoing climate analyses and reanalyses have been emphasized within recent World Meteorological Organization Reports as critical parts of the Global Climate Observing System (GCOS) (*e.g.*, GCOS, 2003, 2004; Simmons *et al.*, 2006 and 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 increased 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, account for different resolutions and sensor measurements, and minimize the impact of transitions between satellite 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, focus on bias-corrected observations, and 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 deleterious impacts of changes in observing systems.

As discussed in Chapter 2, data assimilation techniques used in the first generation of climate reanalyses were developed from methods optimized for use in numerical weather predictions. The primary goal of numerical weather prediction is to produce the best forecast. True "four-dimensional" data assimilation methods (using data in a time window that includes observations from before and after the analysis time) 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 of the analysis time) results 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.

Such constraints are not relevant for climate analyses, and modification of current data assimilation methods may be needed to improve representations of long-term trends and variability (Arkin *et al.*, 2004). Further, many potentially available observations could not be effectively assimilated within the first atmospheric reanalyses, including numerous satellite, surface temperature and precipitation observations (Kalnay *et al.*, 1996). Advances in data assimilation that have occurred in the more than decade since these pioneering reanalysis projects enable better and more complete use of these additional observations. This leads us to our second recommendation.

2. Future efforts should include a focus on developing data assimilation and analysis methods that are optimized for climate purposes, and on providing estimates of uncertainties in all reanalysis products.

It is 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 in this area should be on the post-satellite era, essentially 1979 to present, for which the number and diversity of observational data have expanded greatly, but are yet to be fully utilized. An important development that should facilitate this goal is the national Earth System Modeling Framework (ESMF, <http://www.esmf.ucar.edu/>). The ESMF is a collaborative effort between NASA, NOAA, NSF and DOE that is developing the overall organization, infrastructure, and low-level utilities required to allow the interchange of models, model sub-components, and analysis systems. This development greatly expands the ability of scientists outside the main data assimilation centers (*e.g.*, from universities and other scientific organizations) to accelerate progress toward addressing key challenges required to improve the analyses.

There are a range of climate applications of reanalyses that should be considered and that are likely to require different approaches and assimilation strategies. For example, if the primary goal is to optimize the probability of detection of true climate trends, steps need to be taken to minimize effects of changing observing systems in order to optimize the quality of the analysis over an extended time period. In this case, an appropriate reanalysis strategy may be to use only a subset of high quality, temporally homogeneous data, rather than all available data, over as long a period as feasible. Conversely, if the primary goal is to perform detailed studies of processes at high spatial and temporal resolution, this may require the most accurate analysis at any given time. In this case, an appropriate strategy is to take advantage of all available observations. In either case, uncertainties in the analyses and their implications should be documented appropriately.

Ensemble-based data assimilation techniques, by producing an ensemble of analyses, appear to be especially well suited for providing estimates of uncertainties in the full range of reanalysis products (including, for example, the components of the water cycle such as precipitation and evaporation). Innovative schemes that take advantage of massively parallel computation now make such techniques more economical (*e.g.*, the local ensemble Kalman Filter - Ott *et al.*, 2004). In addition, ensemble-based approaches are being developed that explicitly account for model error (Zupanski and Zupanski, 2006), providing a potentially important step to better estimating analysis uncertainties.

For many research and practical applications, the relatively short period encompassed by the first-generation of reanalyses is another important constraint. Current reanalysis data sets extend back only until the mid-twentieth century, at most. As a consequence, many climate variations of great societal interest are not included in present reanalyses, increasing uncertainties in both their descriptions and causes.

Recent research has demonstrated that a reanalysis through at least the full 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 (GCOS, 2004) and GEOSS (GEOSS, 2005) 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. Such reanalysis data sets should also enable researchers to better address issues on the range of natural variability of extreme events, and increase understanding of how El Niño-Southern Oscillation and other climate modes alter the behavior of these events. This leads to our third recommendation.

3. One stream of reanalysis efforts should focus on producing the longest possible consistent record of surface, near surface, and upper-air variables for the study of global climate variability and change.

Toward this end, alternative assimilation methods should be evaluated for obtaining maximum information for estimating climate variability and trend information from very sparse observations and using only surface observations, for which observational records are available over much longer periods than other data sources. Certain techniques that incorporate 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 also provide estimates of analysis uncertainty. Improved methods of bias estimation and correction, recovery of historical observations, and the development of optimal consistent observational datasets will also be required to support this effort.

In addition to the relatively limited time period, the value of climate analysis and reanalysis data for many practical applications is limited by the coarse horizontal resolution (on the order of 200 km, or approximately 120 miles) of the first-generation reanalysis products, and deficiencies in certain variables (*e.g.*, surface and near variables, precipitation, and the water cycle) that are of great practical interest. As a step forward, NASA's new reanalysis project (MERRA, chapter 2) will provide global reanalyses at approximately 50 km resolution, and has a focus on providing improved estimates of the water cycle <http://gmao.gsfc.nasa.gov/research/merra/>. Another important step forward in this regard is the recently completed North American Regional Reanalysis, or NARR

(Mesinger *et al.*, 2006). While this is a regional, rather than global reanalysis, it is at considerably higher resolution, with a grid spacing of 32 km (about 20 miles). Importantly, NARR also incorporates significant advances in modeling and data assimilation that occurred subsequent to the original global NCEP-NCAR reanalysis (Kalnay *et al.*, 1996), including the assimilation of precipitation observations within the model. This has resulted in substantial improvements in analyzed precipitation, which now agree well with surface observations, and considerable improvements in near-surface temperatures and wind fields (Mesinger *et al.*, 2006). While advances are impressive, initial studies still show deficiencies in our understanding of the water cycle (*e.g.*, Nigam and Ruiz-Barradas, 2006) and representation of convective precipitation (West *et al.*, 2007). The ability to improve analyses of key surface variables and the water cycle remain as important challenges. We therefore make the following recommendation.

4. Another stream of research efforts should focus on producing climate reanalysis products at finer spatial resolution, with increasing emphasis on the quality of products that are of particular relevance for applications, *e.g.*, surface temperatures, winds, and precipitation.

For many users, better representation of the water cycle (inputs, storage, outputs) is a key concern. 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 major research foci as areas for future improvements.

While the first generation of reanalyses focused mainly on the atmospheric component, there is a strong need to consider other Earth System components (such as the ocean, land cryosphere, hydrology and biosphere) as well variables that are of great interest for climate but of less immediate relevance for short-range weather prediction (*e.g.*, the carbon cycle). As discussed in Chapter 2, such efforts are now ongoing for ocean and land data assimilation but are still in relatively early stages. Ultimately, the long-term goal should be to move toward ongoing analyses and periodic reanalyses of all Earth system components relevant to climate variability and change.

Recent efforts to extend initial atmospheric analyses beyond traditional weather variables should provide new information that is highly relevant for decision making and for informing policy response and planning. As one example, the European Union (EU) has funded a new project, the Global Environment Monitoring System (GEMS), that is incorporating satellite and *in situ* data to develop a real-time analysis and forecast capability for 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 high-level policy users, 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 excess deaths (Kosatsky, 2005), mostly due to heat stress but also connected to poor air quality. GEMS will generate a reanalysis of atmospheric dynamics and composition, and state-of-the-art estimates of the sources/sinks plus inter-continental transports, of many trace gases and aerosols. These estimates are designed to meet key information requirements of policy-makers, and be relevant to the Kyoto and Montreal Protocols and the UN 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-ice model for its next generation global reanalysis, extending over the period 1979 to 2008 (S. Saha, personal communication, 2007). The coupled model is based on the NOAA-NCEP Climate Forecast System (CFS) model (Saha *et al.*, 2006). While the updating will be done separately for the different components through independent atmosphere, land and ocean data assimilation systems, the use of a coupled model provides a common "first guess" set of fields that is an important step toward a fully coupled Earth system analysis. Current plans are to begin production and evaluation of the reanalyses 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 over the more than decade since the first-generation NCEP-NCAR reanalysis. Beyond the use of a coupled model, atmospheric resolution will also be greatly increased, from approximately 200 km (120 miles) in the earlier version to 30 to 40 km in the new version. In addition to atmospheric, ocean, and land data assimilation, significant new efforts are examining the use of data assimilation techniques to analyze other aspects of the Earth system, with one important focus being to better represent and identify sources and sinks in the atmospheric carbon cycle (Peters *et al.*, 2005). These developments lead us to the following recommendation.

5. Increasing priority should be given to developing national capabilities in analysis and reanalysis beyond traditional weather variables, and to include effects of coupling among Earth system components.

There is a fundamental need to go beyond traditional weather and climate variables to address many questions relevant to policy and decision support, *e.g.*, analysis and re-analysis of greenhouse gases, other key chemical constituents and aerosols. Future atmospheric climate analyses and reanalyses should increasingly incorporate variables that are of high relevance for decision making and policy development, for example, of the carbon cycle to improve identification of carbon sources and sinks. A reanalysis of the chemical state of the atmosphere would be of benefit for improving understanding of air quality variability and change, aerosol-climate interactions, and other key policy-relevant issues.

Initial attempts at coupling of climate system components, *e.g.*, coupled ocean-atmosphere reanalysis, should be fostered, with a long-term goal being to develop an integrated Earth system analysis (IESA) capability that includes couplings among other system components. An IESA would provide the scientific community, resource managers, decision makers, and policy makers with a high quality, internally consistent, temporally continuous record of the Earth system that can be used to identify, monitor and assess any changes in the system over time. Developing an IESA will also contribute to better describing and understanding coupled processes that may produce accelerated climate changes, *e.g.*, high-latitude feedbacks related to changes in sea ice or melting of permafrost. Key processes include: cryospheric processes, coupled atmosphere-ocean interactions including physical as well as biogeochemical processes, the carbon cycle, and land-biosphere interactions.

Such an effort would clearly crosscut and integrate together most, if not all, of the science elements within the CCSP. It will require an improved capacity to assimilate current and planned future observations from diverse platforms into Earth system models. It is also essential to develop improved understanding of the physical linkages between components, so that how one component affects another can be built into the data assimilation system. This will link analysis capabilities to advances in representing coupled climate processes within Earth system models.

Development of an IESA would therefore directly link together Earth system modeling and Earth system observations within the CCSP. Such an approach is 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 data sets together to obtain a unified, physically consistent description of the Earth system. It also takes advantage of rapid advances in Earth system modeling, as well as providing key feedback on the quality of the models and identification of model deficiencies.

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 the high quality, sustained, cost-effective products. We therefore make the following recommendation.

6. There is a specific and pressing need to go beyond present ad hoc project approaches to develop a more coordinated, effective, and sustained national capability in climate analysis and reanalysis.

Developing a national capability in climate (and more broadly, Earth system) analysis and reanalysis will be essential to achieving key objectives across the Climate Change Science Program 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".

This idea is not new. In fact, it was highlighted over 15 years ago in a National Research Council Report (NRC, 1991) that outlined a strategy for a nationally focused 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 data sets … for the study of climate and global change." This recommendation has been reiterated frequently in several subsequent studies and reports, for example, in a recent interagency-sponsored workshop whose participants included approximately 65 scientists and managers across several Federal agencies, the academic community, and international organizations (Arkin *et al.*, 2004). That workshop concluded that the "U.S. must establish a U.S. National Program for Ongoing Analysis of the Climate System to provide a retrospective and ongoing physically consistent synthesis of Earth observations in order to achieve its climate monitoring, assessment and prediction goals." As discussed in Hollingsworth *et al.* (2005), such an activity is also essential to realizing the full benefits of GEOSS, by transforming Earth system observations into the status-assessment and predictive products required by GEOSS across many areas of socio-economic interest (Figure 4.1).

[Figure 4.1 here]

To be truly successful such a program must be multi-agency, since it requires resources and expertise in a broad range of scientific disciplines and technologies beyond that of any single agency (atmosphere, ocean, land surface and biology, observations and modeling, measurements, computing, data visualization and delivery, *etc.*). 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 ON THE NEED FOR IMPROVED CLIMATE ATTRIBUTION

Recent events speak to the socioeconomic significance of credible and timely climate attribution. For instance, the recent extremely warm year of 2006 raises questions over whether the probability of occurrence of such warm years has changed, the factors contributing to the changes, and how such factors might alter future probabilities of similar (or more extreme) years. Policy and decision makers want to know the answers to such questions, because this information is useful in formulating their planning and response strategies. What climate processes are responsible for the persistent Western United States drought, and what implications does this have for the future? Planners in the West 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 the general increase in activity in this region over the decade beginning in the mid-1990s? Emergency managers want to know the answers to such questions, and related implications for future years.

This assessment report has identified several outstanding challenges in attribution research that are motivated by observed North American climate variations that occurred during the reanalysis period but are yet to be fully explained. For instance, an open question is the cause for 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 signal obtained from coupled model simulations, although model simulations with specified SST variations over the period are able to represent aspects of this pattern. Other forcings, including aerosols, 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 our Nation’s primary grain producing region is a transient condition, *e.g.*, due to a natural multi-decadal variation in ocean conditions that may be masking long-term anthropogenic warming, or whether climate models contain specific errors that are leading to systematic over-estimates 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 detection and attribution of the causes of global-mean surface temperature trends to other key components of the climate system. As detection and attribution studies move toward smaller spatial and temporal scales and consider a broader range of variables than surface temperature, important challenges must be addressed. This section provides recommendations to improve future national capabilities in climate attribution in order to better serve scientific, societal and decision maker needs.

4.4 RECOMMENDATIONS FOR IMPROVING CLIMATE ATTRIBUTION CAPABILITIES

Similar to the present status of United States efforts in climate analysis and reanalysis, attribution research is presently supported in an *ad hoc* fashion, without clear coordination at national or interagency levels (Trenberth *et al.*, 2006). This absence of coordination may limit abilities to address attribution problems of the greatest scientific or public interest. There are also no clear lines to communicate state-of-science findings on attribution. Because of this, the public and media are often exposed to a confusing array of opinions on causes for observed climate events, with diametrically opposed views sometimes expressed by different scientists from within the same agency. In most cases, these statements are made in the absence of any formal attribution studies, and in some cases subsequent attribution research shows that public statements on probable "causes" are extremely unlikely (Hoerling *et al.*, 2007). These considerations, together with scientific limitations identified in Chapter 3, motivate the following recommendation.

7. A national capability in climate attribution should be developed to provide a foundation for regular and reliable explanations of evolving climate conditions relevant to decision making. This will require advances in Earth system modeling, analysis and reanalysis.

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 options and responses in policy and resource management. This capability is also vital to assess climate model performance and to identify where future model improvements are most needed. The associated scientific capacity should include providing coordination of and access to critical observational and reanalysis data sets 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.

Toward developing this capacity, there is a great 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 IPCC Fourth Assessment 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 to store and distribute the very large data sets that were generated from the numerous coupled ocean-atmosphere 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 data sets for model validation; and consistent documentation of climate model features. Providing similar infrastructure support for a broader range of model simulations necessary 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.

As for climate analysis and reanalysis, the continual interplay between observations and models that occurs in attribution studies is fundamental to achieving long-term objectives of the CCSP. Detection and attribution research is vital for providing a rigorous comparison between model-simulated and observed change in both the atmosphere and oceans. To the extent that climate variations and change can be detected and attributed to external forcing factors, the results help to constrain uncertainties in future predictions and projections of climate variations and change. To the extent that climate variations can be attributed to internal forcing factors such as sea surface temperature or soil moisture conditions, the results also help constrain uncertainties in future predictions of climate variations on seasonal to decadal time scales. 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 to identify important model deficiencies and areas where additional effort will be required to reduce uncertainties in climate predictions and climate change projections.

While significant advances have been made 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: 1) uncertainties in observed magnitudes and distributions of forcing from various mechanisms; 2) uncertainties in responses to forcing terms, that is, in the expected "climate signal"; 3) uncertainties in internal natural variability in the system, which is the "climate noise" that would occur even in the absence of changes in the forcing. These considerations lead to the second recommendation.

8. An important focus for future attribution research should be to develop capabilities to better explain causes of climate conditions at regional to local scales, including the roles of changes in land cover/use and aerosols, greenhouse gases, sea surface temperatures, and other forcing factors.

To address the first source of uncertainty, further research is needed to improve observational estimates of changes in radiative forcing factors over a baseline time period, *e.g.*, 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, spatial and temporal scales. For example, land use changes are likely to have a relatively small effect in changing global-mean temperature (*e.g.*, Matthews *et al.*, 2004) but may have more substantial effects on weather locally (*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 scales (Kunkel *et al.*, 2006). Detection and attribution results are sensitive to forcing uncertainties, which can be demonstrated 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. Toward this end, ensemble model experiments should be performed with a diverse set of coupled climate models over a common baseline period, *e.g.*, the twentieth century to present, in which different factors are systematically included or excluded. For example, model simulations with and without changes in observed land cover are needed to better quantify the potential influence of anthropogenic land cover change, especially at regional or smaller scales. Extended control simulations are required with the same models to estimate unforced natural internal variability and assess model climate drifts. The ability to carry out extensive simulations required to more reliably attribute causes of past changes 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 have provided an increased level of confidence in attribution of observed warming between greenhouse gas and sulfate aerosol forcing (Gillett *et al.*, 2002). For a more complete understanding of the effects of forcing and model uncertainty and their representation in detection and attribution, both forcing and model uncertainties need to be explored more completely than at present (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 during the period since 1950. A large and 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. In parallel with the experiments recommended earlier, ensemble experiments should be conducted with the atmospheric components of the models forced by observed sea-surface temperatures over the same baseline time period.

9. A range of methods should be explored 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, as well as potential implications for decision makers (*e.g.*, changes related to probabilistic 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 probabilistic assessments of factors contributing to the relative likelihood of extreme weather and climate events. There is strong need to go beyond present *ad hoc* communication methods to more coordinated 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 for detection and attribution is quantifying the impact of various climate forcings on the probability of specific weather or short-term climate events (see CCSP 3.3, forthcoming). 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.

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 United States warmth of 2006 (Hoerling *et al.*, 2007). Such 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 *ad hoc* 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 climate information system designed to meet the core CCSP objective of providing science-based information for improved decision support.

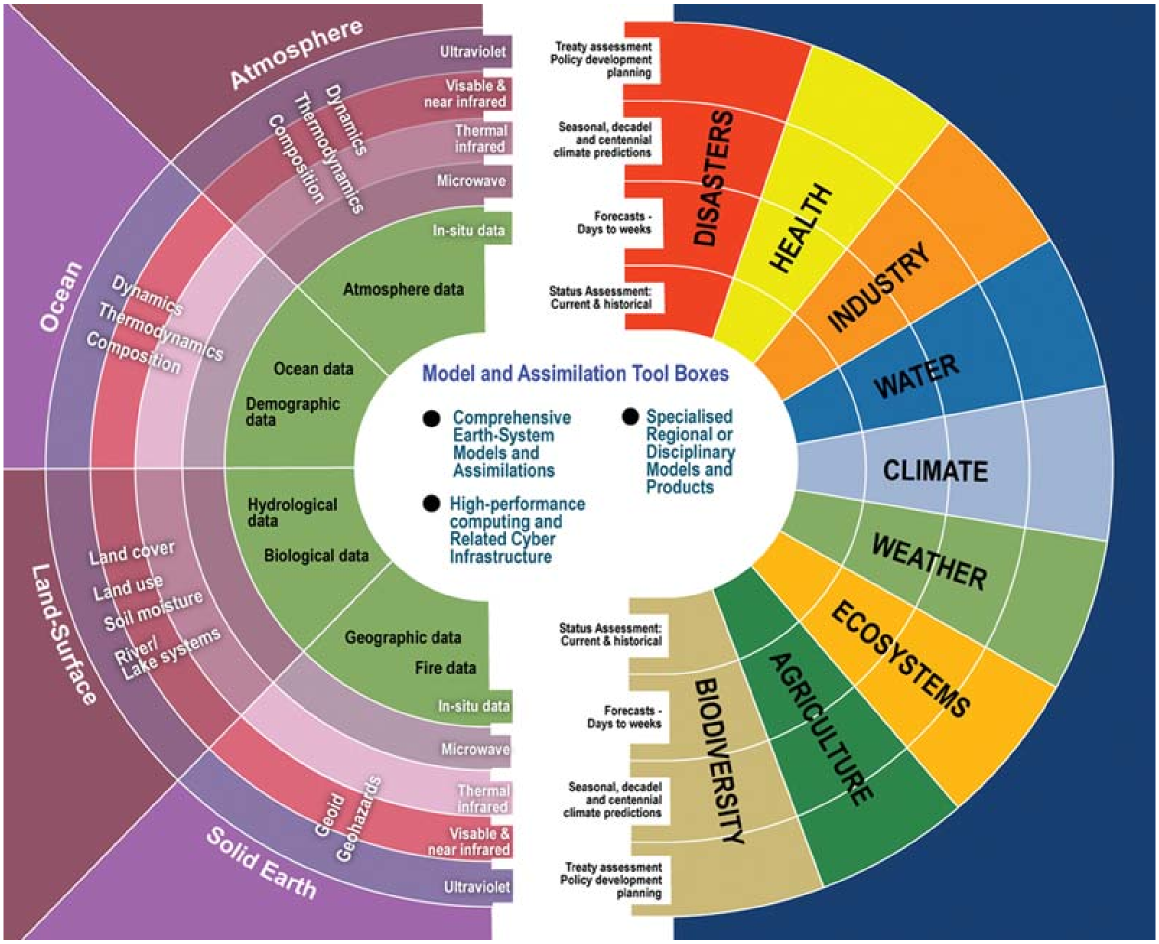

Figure 4.1 From Hollingsworth (2005), based on the GEOSS Implementation Plan (GEOSS, 2005), illustrating the transformation of observations into predictive and current-status information. On the right-hand side are deliverables from an earth system forecasting system and associated specialized models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

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