U.S. Climate Change Science Program

Synthesis and Assessment Product 1.3

Reanalysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change

Lead Agency:
National Oceanic and Atmospheric Administration

Contributing Agencies:
Department of Energy
National Aeronautics and Space Administration

Note to Reviewers: This report has not yet undergone rigorous copy-editing and will do so prior to layout for publication

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CHAPTER 3. ATTRIBUTION OF THE CAUSES OF CLIMATE VARIATIONS AND TRENDS OVER NORTH AMERICA DURING THE MODERN REANALYSIS PERIOD **156**

Abstract

This Climate Change Science Program Synthesis and Assessment Program (SAP) Report addresses current capabilities to integrate observations of the climate system into a consistent description of past and current conditions through the method of reanalysis. In addition, it assesses present capabilities to attribute causes for climate variations and trends over North America during the reanalysis period, which extends from the mid-twentieth century to the present.

This Report reviews the strengths and limitations of current atmospheric reanalysis products for documenting and advancing knowledge of the causes and impacts of global-scale and regional-scale climate phenomena. It finds that reanalysis data play a crucial role in a broad range of climate research problems, in particular those addressing the circulation features and physical mechanisms that produce high-impact climate anomalies such as droughts and floods. Reanalysis data also play a critical role in assessing the ability of climate models to simulate the mean climate and its variations, and in identifying fundamental errors in the physical processes that create climate model biases. The Report finds that current reanalyses have a number of deficiencies that limit their usefulness for climate research and applications. In particular, it highlights the limitations imposed by the inhomogeneous nature of the input observations, and the deficiencies in current climate models in simulating various aspects of the hydrological cycle. The Report emphasizes that significant improvements are possible by developing new methods to address observing system inhomogeneities, by developing estimates of the reanalysis uncertainties, by improving our historical observational database, and by

developing integrated Earth system models and analysis systems that incorporate key climate elements not included in atmospheric reanalyses to date.

The Report provides an assessment of current understanding of causes of observed North American climate variability and trends over the period 1951-2006, based on a synthesis of results from research studies, climate model simulations, reanalysis and observational data. For annual- and area-averaged surface temperatures over North America, more than half of the observed surface warming since 1951 is likely the result of increases in anthropogenic greenhouse gas forcing. However, anthropogenic greenhouse gas forcing alone is unlikely to be the main cause for regional and seasonal differences of surface temperature changes, such as the absence of a summertime warming trend over the Great Plains of the United States, and the absence of a warming trend in both winter and summer over portions of the southern United States. The regional and seasonal variations in temperature trends are related to the principal atmospheric flow patterns that affect North American climate and which are well captured in climate re-analyses. It is likely that variations in regional sea surface temperatures have played an important role in forcing these atmospheric flow patterns, although there is evidence that some flow changes are also due to anthropogenic forcing. In contrast to temperature, there is no discernible trend during this period in annual-average North American precipitation, although there is substantial interannual to decadal variability. Part of the observed interannual to decadal variability in precipitation appears to be related to observed regional variations of sea surface temperatures during this period.

Preface

Convening Lead Author: Dr. Randall Dole, NOAA

A primary objective of the U.S. Climate Change Science Program (CCSP) is to provide the best possible scientific information to support public discussion and government and private sector decision making on key climate-related issues. To help meet this objective, the CCSP has identified 21 Synthesis and Assessment Products (SAPs) that address its highest priority research, observational, and decision-support needs. This SAP Report focuses on the topic of "Re-Analysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change."

P.1 OVERVIEW OF REPORT

New climate observations are most informative when they can be put in the context of what has occurred in the past. Are current conditions unusual, or have they been observed frequently before? Are the current conditions part of a long-term trend, or more likely a manifestation of climate variability that may be expected to reverse over months, seasons, or years? Are similar or related changes occurring in other parts of the globe? What are the processes and mechanisms that can explain current conditions, and how are they similar to, or different from, what has occurred in the past?

The scientific methods of climate re-analysis (henceforth, reanalysis) and attribution are central to addressing such questions. In brief, reanalysis is a method for integrating a diverse array of observations together within a model of the climate system (or of one of its components, such as the atmosphere, ocean, or land surface) to describe past climate conditions over an extended time period, typically multiple decades. An important goal of reanalysis is to provide comprehensive, consistent long-term climate data sets that are reliable on hourly to decadal and longer time scales. Attribution is the process of establishing the most likely cause (or causes) for an observed climate variation or change, and generally involves the use of both observational data and model simulations.

Current reanalysis products provide a foundation for a broad range of weather and climate research. As one measure of their extraordinary research impact, the initial overview paper describing one of the first-generation reanalyses produced in the United States, Kalnay *et al.* (1996), has received 5,300 literature citations as of early 2008, making it the most widely cited paper in the geophysical sciences (ISI Web of Knowledge). A follow-up paper five years later that included a small set of products derived from the same reanalysis (Kistler *et al.*, 2001) has already received nearly 750 citations. Beyond their research applications, reanalysis data are used in an increasing range of commercial and business applications. Some examples include energy (supply/demand analysis), assessing locations for wind power generation, agriculture, water resource management, insurance and reinsurance (*e.g.*, Parry *et al.*, 2007, Chapter 17).

This Report addresses the strengths and limitations of current reanalysis products in documenting, integrating, and advancing knowledge of the climate system. It also assesses our ability to attribute causes for weather and climate variations and trends over North America during the reanalysis period, and discusses the uses, limits and opportunities of improvement of reanalysis data applied for this purpose. The Report is intended to be of value to policymakers in assessing the present state of knowledge with respect to our ability to describe and attribute causes of climate variations and change; for users of reanalysis products in better understanding the strengths and limitations of these products; and for science program managers in developing priorities for future observing, modeling, and analysis systems required to advance national and international capabilities in climate reanalysis and attribution.

Consistent with guidance provided by the Climate Change Science Program, this Report is written primarily for the informed lay reader. For subject matter experts, more detailed discussions are available through the original references cited herein. Because some terms used in this Report will be new to non-specialists, a glossary and list of acronyms is included at the end of this Report.

P.2 PRIMARY REPORT FOCI

This Report considers two general issues of broad interest, within which specific questions are addressed. These are i) the reanalysis of historical climate data for key atmospheric features, in particular, for past climate variations and trends, and ii) attribution of the causes of climate variations and trends over North America during the period from the mid-20th century to present. These topics are described in more detail below.

P.2.1 Reanalysis of Historical Climate Data for Key Atmospheric Features

The availability and usefulness of reanalysis data has led to many important scientific advances, as well as a broad range of new applications. However, limitations of past and current observations, models, and reanalysis methods have also contributed to uncertainties in describing climate system behavior. Chapter 2 of the Report focuses on the strengths and limitations of current reanalysis data for identifying and describing past climate variations and trends. The "first-generation" climate reanalyses developed over the past decade focused on reconstructing past atmospheric conditions from the second half of the twentieth century to the present. Because of the greater maturity and more extensive use of these atmospheric reanalyses, they constitute the primary focus of this Report. However, efforts are now underway to create reanalyses for the ocean and land surface, and so emerging capabilities in these areas will also be briefly discussed.

The specific questions addressed in this Chapter are:

- What is a climate reanalysis, and what role does reanalysis play within a comprehensive climate observing system?
- What can reanalysis tell us about climate forcing and the veracity of climate models?
- What is the capacity of current reanalyses to help us identify and understand major seasonal-to-decadal climate variations, including changes in the frequency and intensity of climate extremes such as droughts?

- To what extent is there agreement or disagreement between climate trends in surface temperature and precipitation derived from reanalyses and those derived from independent data?
- What steps would be most useful in reducing spurious trends and other major uncertainties in describing the past behavior of the climate system through reanalysis methods? Specifically, what contributions could be made through improvements in data recovery or quality control, modeling, or data assimilation techniques?

This part of the Report should prove useful for science program managers in developing priorities to reduce uncertainties and improve capabilities to describe past and ongoing climate variability and change through reanalysis methods. The assessment of capabilities and limitations of current reanalysis products should also be of value to users of reanalysis products.

P.2.2 Attribution of the Causes of Climate Variations and Trends Over North America

Chapter 3 discusses progress and limits in our understanding of the causes of climate variations and trends over the North American region from the mid-twentieth century to the present, the time period encompassed by current atmospheric reanalysis products. It also addresses strengths and limitations of reanalysis products in supporting research to attribute the causes of climate variations and trends over North America during this time period. The specific questions considered in this Section are:

- What is climate attribution, and what are the scientific methods used for establishing attribution?
- What is the present understanding of the causes for North American climate trends in annual temperature and precipitation during the reanalysis record?
- What is the present understanding of causes for seasonal and regional variations in United States temperature and precipitation trends over the reanalysis record?
- What is the nature and cause of apparent rapid climate shifts, having material relevance to North America, over the reanalysis record?
- What is our present understanding of the causes for high-impact drought events over North America over the reanalysis record?

The primary audience for this Section is policymakers, who will have an improved basis for ascertaining the present state-of-knowledge and key remaining uncertainties in attributing the causes of major climate variations and trends over North America and the United States during the past half-century. Resource managers and other decision makers, as well as the general public, may also benefit from a report assessing our present understanding of the causes of past climate variations and trends, especially those events that have high societal, economic, or environmental impacts, such as major droughts.

The concluding Chapter of this Report (Chapter 4) discusses steps needed to improve national capabilities in 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. This Chapter may be of particular interest to scientists and research program managers who are engaged in efforts to advance national and international capabilities in climate reanalysis and attribution.

P.3 TREATMENT OF UNCERTAINTY

In this Report, terms used to indicate the assessed likelihood of an outcome are consistent with those used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007). This terminology is summarized in Table P.1:

Table P.1 IPCC AR4 terminology - likelihood of outcome.

Likelihood Terminology	**Likelihood of occurrence/outcome**
Virtually Certain	> 99% probability
Extremely Likely	> 95% probability
Very Likely	> 90% probability
Likely	> 66% probability
More Likely than Not	> 50% probability
About as Likely as Not	33% to 66% probability
Unlikely	< 33% probability
Very Unlikely	< 10% probability
Extremely Unlikely	< 5% probability
Exceptionally Unlikely	< 1% probability

Terms denoting levels of confidence on findings are also consistent with AR4 usage, as specified in Table P.2:

Table P.2 IPCC AR4 terminology - degree of confidence.

Terminology	**Degree of confidence in being correct**
Very High Confidence	At least 9 out of 10 change of being correct
High Confidence	About 8 out of 10 chance
Medium Confidence	About 5 out of 10 chance
Low Confidence	About 2 out of 10 chance
Very Low Confidence	Less than 1 out of 10 chance

P.4 SCOPE AND LIMITATIONS OF THIS REPORT

The time period considered in this Report for describing and attributing the causes of climate variations and trends is limited to that of present-day reanalysis records, which extend from approximately 1950 to the present. As discussed in the concluding Chapter, an effort is now underway to extend reanalysis data back to at least the latter part of the 19th century. While initial results appear promising, this extended reanalysis project is not yet completed and so it is premature to assess results of this effort within this Report.

As with any report of this type, the findings described here provide a snapshot of the state-of-science at a given time; in this case, as of mid-2007. The fields of climate analysis, reanalysis, and attribution are cutting edge areas of climate research, with new results being obtained every month. Hence, within the next few years new results are likely to appear that will supersede some of this Report's findings; for example, with respect to the quality, types and lengths of reanalysis records that are available.

Finally, in preparing this Report, its scope was considered in light of other ongoing assessments, especially the recently completed IPCC AR4 report and other synthesis and assessment reports being developed within the Climate Change Science Program. While it is inevitable, and perhaps even desirable, that there be some overlap with these other assessments, we have attempted to minimize duplication and to focus on issues of special relevance to the intended audience. Thus, while the IPCC AR4 Working Group I report (Solomon *et al.*, 2007) devotes a chapter to understanding and attributing climate change (Hegerl *et al.*, 2007), that report primarily emphasizes changes at global to continental scales, whereas in this Report the focus is on the United States/North American sector and considers regional climate variations and trends of specific interest to the United States public and decision makers.

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Executive Summary

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Among the most common questions that climate scientists are asked to address are: What are current climate conditions? How do these conditions compare with the past? What are the causes for current conditions, and are the causes similar to or different from those of the past? This Climate Change Science Program (CCSP) synthesis and assessment Report summarizes how climate science can be used to address such questions, focusing on advances obtained through the methods of re-analysis (henceforth, reanalysis) and attribution.

In brief, a reanalysis is an objective, quantitative method for representing past weather and climate conditions, including various components of the climate system, such as the atmosphere, oceans or land surface. An important goal of most reanalysis efforts to date has been to reconstruct as accurately as possible the evolution of the global atmosphere, usually at time steps of every 6 to 12 hours, over time periods of decades or longer. The reanalysis efforts assessed in this Report estimate past conditions through a method that integrates observations derived from numerous data sources within a sophisticated Earth System model (or a model of one of its components, such as the atmosphere, ocean, or land surface). As such, the methods described in this Report fundamentally link climate observations and models. Through this approach, several comprehensive, high quality, temporally continuous, and physically-consistent climate analysis data sets have been developed that typically span the entire globe (or large subregions, such as North America) over time periods of decades or longer.

This Report addresses the strengths and limitations of current climate reanalysis products in documenting, integrating, and advancing scientific knowledge of the climate system. It then assesses current capabilities and uncertainties in our ability to attribute causes for climate variations and trends over North America during the reanalysis period, which extends from the mid-twentieth century to the present. It concludes with recommendations for improving the scientific and practical value of climate reanalyses, and suggests additional priorities for reducing uncertainties in climate attribution and realizing the benefits of this information for decision support.

This Report represents a significant extension beyond the recently completed Inter-governmental Panel on Climate Change (IPCC) Fourth Assessment Report. While the IPCC report mainly emphasized detection and attribution of the causes for climate variations and trends at global to continental scales, this Report focuses primarily on the United States and North America sector, including regional climate variations and trends that are of substantial interest to the United States public, decision makers, and policy makers.

ES.1 PRIMARY RESULTS AND FINDINGS

ES.1.1 Strengths and Limitations of Current Reanalysis Data Sets for Representing Key Atmospheric Features (From Chapter 2).

- Reanalysis plays a crucial integrating role within a global climate observing system by producing comprehensive long-term, objective, and internally consistent records of climate system components, including the atmosphere, oceans, and land surface. The long-term records created through reanalyses provide a fundamental and unique contribution in enabling research that addresses the nature, causes and impacts of global-scale and regional-scale climate phenomena.
- Reanalysis data sets are of particular value in studies of the mechanisms that produce high-impact climate anomalies such as droughts, as well as other key atmospheric features that affect the United States, including climate variations associated with El Niño-Southern Oscillation and other major modes of climate variability.
- Observed global and regional surface temperature trends are captured to first order in reanalysis data sets, particularly since the late 1970s, although some regions continue to show major differences with observations (*e.g.*, Australia).
- Reanalysis precipitation trends are much less consistent with those calculated from observational datasets, likely due principally to reanalysis model deficiencies.

- The overall quality of reanalysis products varies with latitude, height, time period, spatial and temporal scale, and quantity or variable of interest. Specifically,
    - Current global reanalysis data are most reliable in Northern Hemisphere mid-latitudes, in the middle to upper troposphere, and on regional and larger spatial scales. They are least reliable near the surface, in the stratosphere, tropics, and in polar regions.
    - Current global reanalyses are most reliable from a few days to interannual time scales. They are least reliable at representing features evolving within one day, such as the diurnal cycle, and on decadal and longer time scales.
    - Current reanalysis data are most reliable in quantities that are strongly constrained by observations, and least reliable for quantities that are highly model dependent, such as precipitation, evaporation, and cloud-related quantities.
- Substantial biases exist in the simulated components of the atmospheric water cycle that limit the value of current reanalysis data for assessing the veracity of these quantities in climate models, as well as for many practical applications. There are also biases in other surface and near-surface quantities related to deficiencies in the representation of interactions across the land-atmosphere and ocean-atmosphere interfaces.
- In addition to model biases, deficiencies in the coverage and quality of observational data and changes in observing systems over time reduce the reliability of reanalyses (as well as other data sets) for studies of decadal and longer-term climate changes.

Despite their limitations, the integrated, comprehensive and multivariate nature of reanalysis data are of value for understanding the mechanisms for surface temperature and precipitation trends, beyond what can be determined from the observational datasets of temperature or precipitation alone. Reanalysis products are also of considerable value in assessing climate models used to simulate and predict climate variations and change.

Substantial future improvements in reanalysis products can be achieved through a number of actions, including developing new methods to address changes in observing systems, improving the observational database, and developing integrated Earth System models and analyses that incorporate additional atmospheric constituents and other climate-relevant processes that are not present in current products. Recommendations for increasing the scientific and practical value of climate analyses and reanalyses are summarized at the end of this section and discussed in more detail in Chapter 4.

This Report also considers causes of climate variations and trends over North America during the modern reanalysis period, which extends from the mid-twentieth century to the present. The emphasis is on regional features that have particular relevance to the United States public, decision makers and policy makers. Five specific questions are addressed in Chapter 3 on assessing the causes of key features of observed North American climate variations and trends since 1950.

ES.1.2 Attribution of the Causes of Climate Variations and Trends Over North America During the Modern Reanalysis Period (From Chapter 3)

ES.1.2.1 North American area- and annual-average surface temperatures and precipitation

- Since 1951 (the beginning of the time period assessed in this Report), seven of the warmest ten years have occurred in the last decade (1997-2006). The 56-year linear trend (1951-2006) of area- and annual-average surface temperature is +0.90°C +/-0.1°C. Virtually all of this warming has occurred since 1970.
- More than half of the North American warming since 1951 is *likely* the result of anthropogenic forcing. This assessment is based on the synthesis of findings that include results from 19 state-of-the-art climate models subjected to combined anthropogenic and natural forcing of 1951-2006, all of which yield warming greater than half that observed, whereas only 5 of 76 samples of 56-year trends obtained from model runs with natural forcing alone produced warming of at least half that observed. In addition, none of the 76 samples of 56-year trends based on model simulations that used natural forcing alone produced warming as large as observed.
- There is no significant trend in North American precipitation since 1951, although there is substantial interannual to decadal variability. Part of the observed interannual to decadal variability appears to be related to observed variations of regional sea surface temperatures during this period.

ES.1.2.2 North American regional temperatures and precipitation

- The largest annual-mean regional temperature increases have occurred over northern and western North America. During summertime, no significant temperature change has occurred over the Great Plains of the United States, nor warming over portions of the southern United States and eastern Canada during winter and summer. Changes in free atmospheric circulation as identified in reanalysis datasets provide the *likely* dominant physical mechanism for explaining differences in regional surface temperature trends, especially during winter.
- The regional differences in surface temperature trends across North America are *unlikely* to be the result of anthropogenic forcing alone, but *likely* have been influenced by regional sea surface temperature variations over the period. The extent to which regional sea surface temperature variations are due to anthropogenic forcing is not assessed in this Report. This attribution is based on a synthesis of findings that include results from the ensemble average of 19 climate models subjected to combined anthropogenic and natural forcing of 1951-2006, which fail to produce either the observed regional variations in North American surface temperature trends or the atmospheric circulation pattern that is associated with the regional surface temperature changes, especially during winter. These features are produced, however, in atmospheric models forced only with the observed sea surface temperature variations since 1951.
- The regional and seasonal differences in precipitation variability are *unlikely* to be the result of anthropogenic forcing alone. Some of the regional and seasonal precipitation variations that have occurred are instead *likely* to be the result of

regional variations in sea surface temperatures through their influence on the atmospheric circulation. This attribution is based on a synthesis of findings that include results from the ensemble average of 19 climate models subjected to combined anthropogenic and natural forcing of 1951-2006 compared with atmospheric models forced only with the observed sea surface temperature variations since 1951.

ES.1.2.3 North American droughts

- It is *unlikely* that a systematic change has occurred in either the frequency or area coverage of severe drought over the conterminous United States during the past half-century. This assessment is based on peer-reviewed literature analyzing modern and paleo-reconstructions of drought, which indicates that the area covered by severe drought during the study period of this Report has not been unusual, being marked by large interannual to decadal variability but no clear trends. There is, however, published evidence that anthropogenic forcing may be creating conditions more favorable for drought over portions of North America, *e.g.*, the southwestern United States, and that increasing land surface temperatures are adding to water stress during droughts.

ES.2 RECOMMENDATIONS

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

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.

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.

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.

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.

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.

The following additional priorities are recommended for reducing uncertainties in climate attribution and realizing the benefits 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.

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.

9. A range of methods should be explored to better quantify and communicate findings from attribution research.

Chapter 1. Fundamental Concepts

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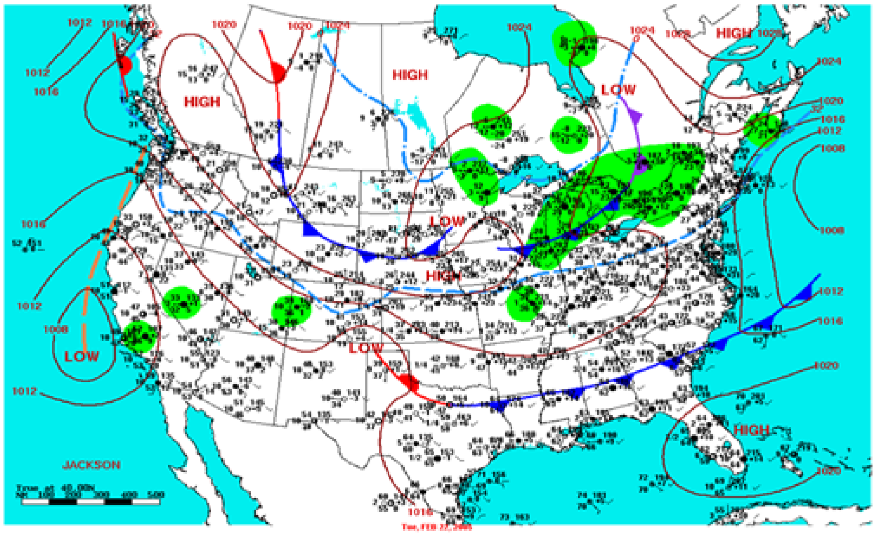
FUNDAMENTAL CONCEPTS

Among the most frequent questions that the public and decision makers ask climate scientists are: What do we know about past climate? What are our uncertainties? What do we know about the causes of climate variations and change? What are our uncertainties on causes? The scientific methods of climate re-analysis (henceforth, **reanalysis**) and **attribution** play important roles in helping to address such questions. This Chapter is intended to provide readers with an initial foundation for understanding the nature and scientific roles of reanalysis and attribution, as well as their potential relevance for applications and decision making. These subjects are then discussed in detail in the following chapters.

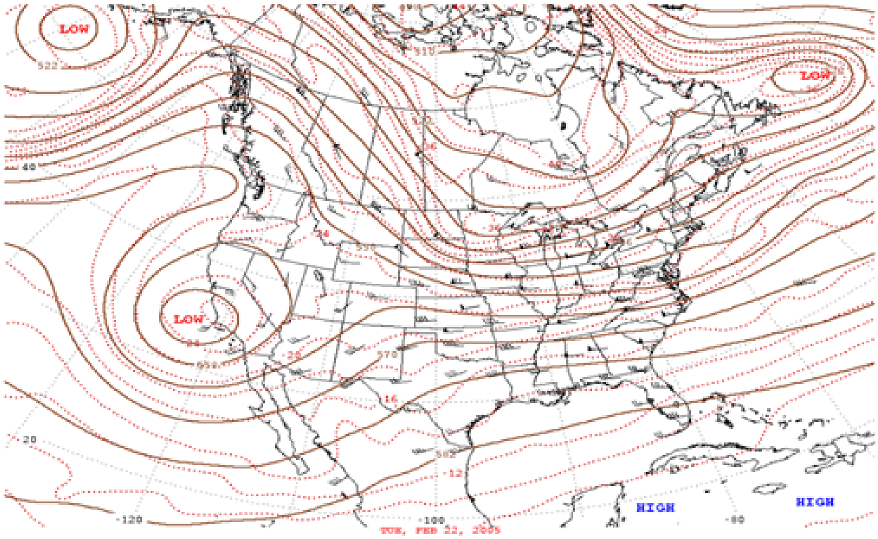
1.1 REANALYSIS

In atmospheric science, an analysis is a detailed representation of the state of the atmosphere and, more generally, other components of the climate system (such as oceans or land surface) that is based on observations (Geer, 1996). The analysis is often depicted as a map of the values of a variable (*e.g.*, temperature, winds or precipitation) or set of variables for a specific time, level and spatial domain, for example, over the United

States, the Northern Hemisphere, or the globe. The daily "weather maps" that are presented in newspapers, on television and in numerous other sources are familiar examples of this form of analysis (Figure 1.1).



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.



500-Millibar Height Contours at 7:00 A.M. E.S.T.

Figure 1.1 Examples of map analyses for a given day (February 22, 2005) for the continental United States and adjacent regions. *Top figure:* surface weather analysis, or "weather map". Contours are lines of constant pressure (isobars), while green shaded areas denote precipitation. Positions of low and high pressure centers, fronts and a subset of surface station locations with observations are also shown. *Bottom figure:* a map of the heights (solid lines, in decameters) and temperatures (dotted lines, in ^{o}C) of a constant pressure surface that represents conditions in the middle troposphere, and is often indicative of the position of the jet stream. The symbols with bars and/or pennants show wind speeds and directions obtained from observations. Wind directions "blow" from the end with bars toward the open end, the latter depicting the observation station location (*e.g.*, winds over Denver on this day are from the west, while those over Oakland are from the east). Note that there is a very pronounced tendency for the upper level winds to blow parallel to the constant height contours, an example of a balance relationship that is used to help construct the analyses, as discussed in Chapter 2.

A *reanalysis,* then, is an objective, quantitative method for producing analyses of past weather and climate conditions, including various components of the climate system, such as the atmosphere, oceans or land surface. An important goal of most reanalysis efforts to date has been to construct a more accurate and consistent long-term data record of the global atmosphere than provided by analyses developed for other purposes, *e.g.*, for preparing weather forecasts, which are strongly constrained by the practical need to produce forecasts within a very short time window (often one to two hours or less), and therefore cannot fully use all potential observations. For certain purposes, a reanalysis may be performed for a single variable, for example, precipitation or surface temperature (Fuchs, 2007). However, in many modern atmospheric reanalyses the central goal is to develop an accurate and physically consistent representation of the extensive set of variables (*e.g.*, winds, temperatures, pressures, and so on) required to fully describe the state of the atmosphere and how it has evolved over time. *It is such comprehensive reanalyses that are the subject of this assessment.*

The reanalysis efforts assessed in this Report estimate past conditions through a method that integrates observations derived from numerous data sources (Figure 1.2) within a sophisticated Earth System model (or a model of one of its components, such as the atmosphere, ocean, or land surface). As such, the methods described in this Report fundamentally link climate observations and models. This data-model integration provides a comprehensive, high quality, temporally continuous, and physical consistent climate data set. Physical consistency is obtained through the use of the model, which constrains the analysis to be consistent with the fundamental laws that govern the atmosphere (or other climate system component, like the ocean). Details of this process are described in Chapter 2. The atmospheric reanalyses assessed in this Report typically span the entire globe and extend from the surface up to high levels in the atmosphere, *e.g.*, up through 95% or more of the atmosphere's mass. They provide a detailed record of how the atmosphere has evolved at time steps of every 6 to 12 hours over periods spanning multiple decades. Henceforth in this Report, unless stated otherwise, the term *reanalysis* refers to this method for reconstructing past states of the atmosphere or of other climate system subcomponents, such as the ocean or land surface.

Figure 1.2 An illustration of some of the diverse types of observational systems that provide data used to construct a weather or climate analysis. Examples of data sources include geostationary and polar-orbiting satellites, aircraft, radar, weather balloons, ships at sea and offshore buoys, and surface observing stations. Numerous other observational systems not shown here also provide data that is integrated together to produce a comprehensive climate system analysis.

Chapter 2 describes in detail reanalysis methods and the strengths and limitations of current reanalyses when used for a range of applications, including the detection of major climate variations and trends. Specific questions addressed in that chapter are:

- What is a climate reanalysis, and what role does reanalysis play within a comprehensive climate observing system?
- What can reanalysis tell us about climate forcing and the veracity of climate models?

- What is the capacity of current reanalyses to help us identify and understand major seasonal-to-decadal climate variations, including changes in the frequency and intensity of climate extremes such as droughts?
- To what extent is there agreement or disagreement between climate trends in surface temperature and precipitation derived from reanalyses and those derived from independent data?
- What steps would be most useful in reducing spurious trends and other major uncertainties in describing the past behavior of the climate system through reanalysis methods? Specifically, what contributions could be made through improvements in data recovery or quality control, modeling, or data assimilation techniques?

1.2 ATTRIBUTION

The term *attribute* has as a common use definition "To assign to a cause or source" (Webster's II Dictionary, 1988). This is also the general sense used in this Report. The Intergovernmental Panel on Climate Change (IPCC) has more specifically stated that: "attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some level of confidence" (IPCC, 2007). The use of the term attribution in this Report is similar to that of the IPCC definition. However, *here the scope is broadened to include climate variations as well as detected climate change*, because identifying the causes of climate variations is also of significant public interest. Such variations can have very large economic impacts (NCDC reports at <http://www.ncdc.noaa.gov/oa/reports/billionz.html>, and likely will be important in modulating effects of any future climate changes (Parry *et al.*, 2007). While it is difficult, if not impossible, to attribute an individual climate event or fluctuation solely to one specific cause, climate attribution also involves determining how the probability of occurrence of a specific event (*e.g.*, a prolonged drought) may be altered in response to a particular forcing, for example, due to changes in sea surface temperatures, volcanic aerosols or greenhouse gas emissions (Stott *et al.*, 2004). As part of this effort, reanalysis data are being used increasingly by climate scientists in studies of processes that produce observed climate variations, as well as in assessing the quality and veracity of climate models used in evaluating potential mechanisms for climate variations and change.

In Chapter 3, the uses of reanalysis and other methods of climate science are discussed for attributing the causes of observed climate variations and trends. The time period considered in this Report is limited to that of current reanalysis records, which extend from approximately 1950 to the present, with a geographical focus on the North American region. The specific questions considered in Chapter 3 are:

- What is climate attribution, and what are the scientific methods used for establishing attribution?
- What is the present understanding of the causes for North American climate trends in annual temperature and precipitation during the reanalysis record?
- What is the present understanding of causes for seasonal and regional variations in United States temperature and precipitation trends over the reanalysis record?
- What is the nature and cause of apparent rapid climate shifts, having material relevance to North America, over the reanalysis record?

- What is our present understanding of the causes for high-impact drought events over North America over the reanalysis record?

1.3 CONNECTIONS BETWEEN REANALYSIS AND ATTRIBUTION

What are the scientific connections between reanalysis and attribution and, specifically, why might reanalysis be useful for developing attribution? While there are numerous connections, to provide some initial insight it may be helpful to first consider an analogy from an area that is perhaps more familiar to most readers. Figure 1.3 illustrates schematically some key steps in establishing a medical diagnosis, and corresponding analogues to steps commonly employed in climate science, including reanalysis and attribution.

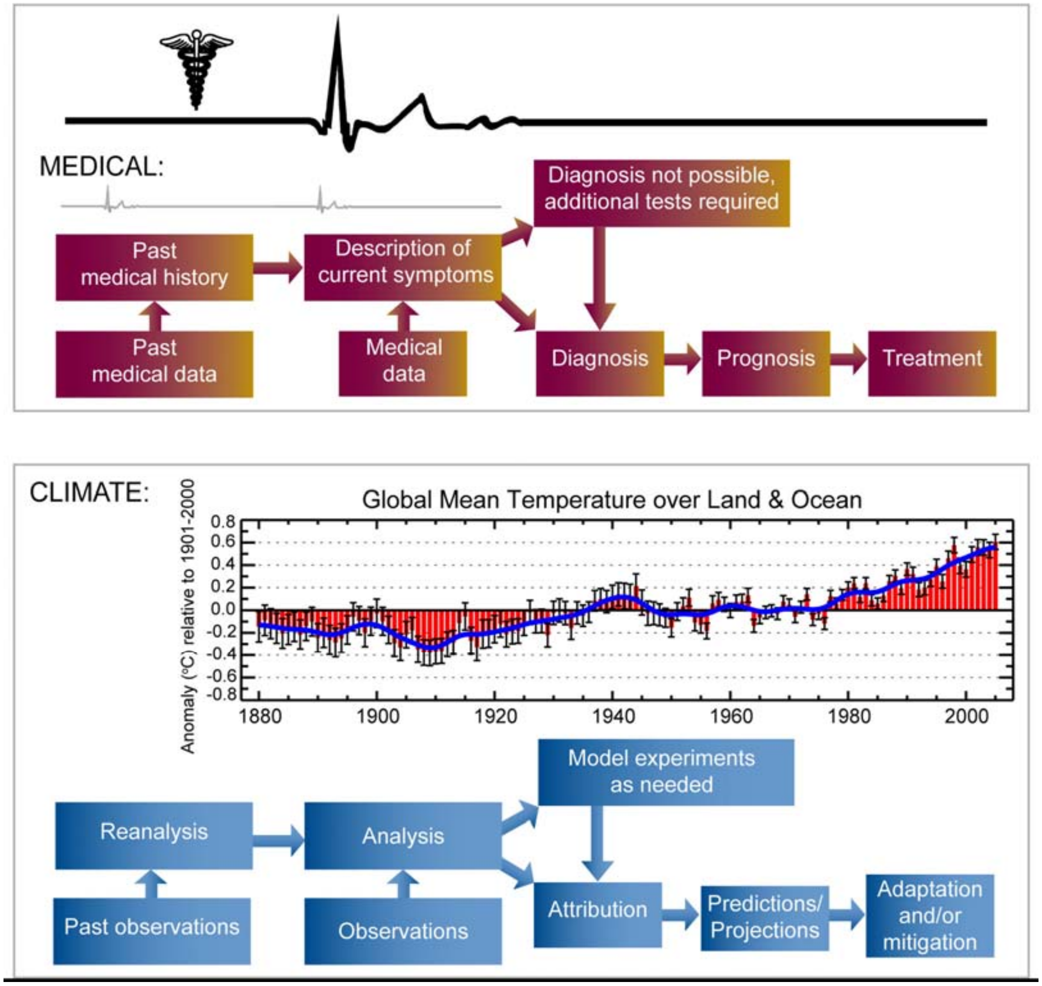


Figure 1.3 Schematic illustrating the analogy between approaches used in medicine and climate science, as discussed in the text.

1.3.1 Medical Diagnosis

Consider a patient visiting a doctor's office for possible treatment of an illness. The usual first step in the process is to collect a set of basic measurements - temperature, blood pressure, and so on - together with other information on the patient's condition (Figure 1.3, top). In medical practice, the initial information together with medical knowledge (*i.e.*, a medical "model") is used to assess the patient's health status at that time. A further important step is consideration of the patient's medical history, including comparison with baseline information and identification of key changes over time. The physician uses this information on current conditions and past history in helping to establish a medical diagnosis. In many cases, diagnosis may not be possible from this information alone, in which case the physician performs additional tests to determine the cause of the illness.

In climate science, the analogous initial steps are the collection of climate observations from diverse observing systems, together with construction of a climate analysis that depicts the climate state at a given time (Figure 1.3, bottom). Reanalysis then corresponds to the medical step of carefully reconstructing the patient's past history. This reanalysis should preferably be done with consistent data and methods in order to accurately identify changes over time, as well as how changes in different system components are related. In climate science, attribution corresponds directly with the medical step of diagnosis and, as in the medical example, additional "diagnostic tests" are often required. In climate science, these additional tests frequently consist of controlled experiments conducted with climate models, where results are compared between model outcomes when a forcing of interest (say, from greenhouse gases or aerosols) is either included or excluded in order to assess its potential effects.

In medical science, establishing a diagnosis is fundamental to developing a prognosis for the illness and considering options for treatment. Similarly, in climate science establishing attribution provides a scientific underpinning for predicting future climate, as well as information useful for evaluating needs and options for adaptation and/or mitigation. While detailed discussions of climate prediction, adaptation and mitigation are beyond the scope of this Report, recognition of such relationships helps illuminate the potential value and applications of climate reanalysis and attribution.

1.3.2 Relationships in Climate Science

As illustrated by the above example, observations serve as the fundamental starting point for climate reanalysis. A perhaps more subtle point is that, in general, observations themselves are not sufficient to establish attribution; models incorporating our understanding of key physical processes and relationships are also required. For attribution to be meaningful, the condition of interest (*e.g.*, a long-term trend or other feature, such as a severe drought) must first be identified with statistical confidence in the data record. Reanalysis can, and often does, play a vital role in this regard, by providing a comprehensive, high quality, temporally continuous, and physically consistent climate data set spanning multiple decades. Physical consistency, obtained through the use of a model that incorporates the fundamental laws governing the atmosphere (or other climate system component, like the ocean), is also a primary feature of reanalysis data sets. This physical consistency enables identification of the roles of various key processes in producing climate variations and change, along with corresponding linked patterns of variability. For example, it can enable comparisons of the relative roles of different physical processes in producing patterns of wind, temperature or precipitation variability. The method of reanalysis can therefore also contribute to more confident interpretations of the mechanisms that produce responses within climate system to a given forcing, and demonstrate how and why the responses may be far removed geographically from the source of the forcing itself (*i.e.*, a non-local response).

In climate science, reanalysis has important connections to the fundamental problem of detecting climate change (or variability). Within the IPCC, detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, *without providing a reason for that change.* As stated earlier, attribution of the causes of climate change is the process of establishing the most likely causes for the detected change with some level of confidence. While reanalysis can play an important role in both detecting and attributing causes of climate variations and change, it is vital to recognize that this method alone is seldom sufficient, and that best practices for both detection and attribution often depend on results obtained from a broad range of data sets, models, and analysis techniques. For example, for detecting surface temperature changes, specialized data sets focused on this variable alone are likely to be superior to more general reanalysis data sets, although even different specialized sets may not fully agree among themselves, depending on techniques used and other factors (see Chapter 2).

While such specialized sets are often superior for detecting changes in individual variables, in themselves they provide few (if any) insights into the causes of the changes. Here, the more complete and consistent reanalysis data are generally much more useful in helping to establish the connections among changes in different system variables; for example, how surface temperature changes are related to changes in winds over the same period. Identification of these relationships can provide important insights on key mechanisms, but may not be sufficient to establish ultimate causes. In order to establish more definitive attribution, climate scientists usually must also perform sets of controlled experiments with climate models to determine whether estimated responses to particular forcings are consistent in a statistical sense with observed patterns of variability or change, or may be consistent with purely internal variations in the system (unforced variability). Beyond demonstrating consistency of expected and observed responses, there is a need to demonstrate that the observed changes are not consistent with "alternative, physically plausible explanations . . . that exclude important elements of the given combination of forcings" (IPCC, 2001). As noted in Chapter 3, reanalysis data sets can also be very useful in providing important checks on whether climate models are consistent in representing observed behaviors in the climate system and whether they display adequate sensitivity in their responses to different forcing mechanisms.

The limitations of observational data, analysis techniques and models all produce sources of uncertainties, as discussed in Chapters 2 and 3. Because of this, detection and attribution of causes of climate change must ultimately be stated in probabilistic terms, and expert judgment is often required to assess the weight of evidence on particular mechanisms and remaining uncertainties (see Chapter 3). As stated in the preface, the language on uncertainty adopted in this Report is consistent with that used in the most recent IPCC assessment. In addition, it is important to recognize that in complex systems, whether human, biological, or physical, it is often not a single factor but, rather, the interactions among multiple factors that determine the ultimate outcome.

1.4 REANALYSIS APPLICATIONS AND USES

Over the past several years, reanalysis data sets have become a cornerstone for research in advancing our understanding of how and why climate has varied over roughly the past half-century. As one measure of their extraordinary research impacts, the initial overview paper on one of the first-generation reanalysis data sets produced in the United States, Kalnay *et al.* (1996), has been cited over 5,300 times in the peer-reviewed literature as of early 2008, and is now ranked as the most widely cited paper in the geophysical sciences (ISI Web of Knowledge, <http://www.isiwebofknowledge.com/>). Reanalysis data are used for an extensive range of scientific purposes. A few examples include: climate change detection research (Santer *et al.*, 2003); identification and description of modes of climate variability (Thompson and Wallace, 1998, 2000, 2001; Hurrell *et al.*, 2004; Hoerling *et al.*, 2004); studies of climate extremes (Nogaj *et al.*, 2006); and assessments of climate predictability (Sardeshmukh *et al.*, 2000; Winkler *et al.*, 2001; Newman *et al.*, 2000; Compo and Sardeshmukh, 2004). Reanalysis has shown its strongest and most impressive results where the physical consistency between climate variables is important (for instance, the relationship between pressure and wind), and where these relationships can be well sampled over the available time period, for example, over days to seasons. In contrast, when results are sensitive to changes in observing systems, as in the detection of climate trends for certain variables, reanalyses can be of more limited value and may show spurious trends (Chelliah and Ropelewski, 2000; Chapter 2 of this Report).

Increasingly, reanalysis data sets and their derived products are also being used in a wide range of practical applications. One important application is to aid in comparing current and past climate; in essence, to address the question: "How is the present climate similar to, or different from, past conditions?" The high temporal resolution of reanalysis data (typically, every 6-12 hours) enables detailed study of the time evolution of individual weather and climate events and comparisons with similar events in the past, providing important clues on physical mechanisms. As discussed in Chapter 2, intercomparisons of different reanalyses and observational data sets also provide a measure of part of the uncertainty in representations of past climate, including identifying phenomena, regions and time periods for which confidence in the representations is relatively high or low (Santer *et al.*, 2005).

Beyond these scientific applications, reanalysis data sets are beginning to see increased use for practical applications in areas such as energy (*e.g.*, assessing locations for wind power generation), agriculture, insurance and reinsurance, and water resource management (Pulwarty, 2003; Parry *et al.*, 2007, Chapter 17). Indeed, a relatively new high-resolution reanalysis, the North American Regional Reanalysis (Mesinger *et al.*, 2006), had as an important focus to improve the representation of the water cycle over North America to better serve water resource management needs. The assessment of reanalysis efforts in Chapter 2 of this Report should help to inform users of strengths and limits of current reanalysis data sets, and to aid in understanding whether certain data sets are suited for specific purposes. Chapter 3 addresses the problem of attributing causes for observed climate variations and change over North America during the period from the mid-twentieth century to the present, including uses and limits of reanalysis methods for this specific purpose. Chapter 4 concludes the Report with a discussion of steps needed to improve national capabilities in reanalysis and attribution in order to increase their value for applications and decision making.

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Chapter 2. Re-Analysis of Historical Climate Data for Key Atmospheric Features

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KEY FINDINGS

- Reanalysis plays a crucial integrating role within a global climate observing system by producing comprehensive long-term, objective, and consistent records of climate system components, including the atmosphere, oceans, and land surface (Section 2.1).
- Reanalysis data play a fundamental and unique role in studies that address the nature, causes and impacts of global-scale and regional-scale climate phenomena (Section 2.3).
- Reanalysis data sets are of particular value in studies of the physical mechanisms that produce high-impact climate anomalies such as droughts and floods, as well as other key atmospheric features that affect the United States, including climate variations associated with El Niño-Southern Oscillation and other major modes of climate variability (Section 2.3).

- Observed global and regional surface temperature trends are captured to first order in reanalysis data sets, particularly since the late 1970s, although some regions continue to show major differences with observations (*e.g.*, Australia). Reanalysis precipitation trends are much less consistent with those calculated from observational datasets, probably due to deficiencies in current global reanalysis models (Section 2.4).
- While current reanalysis data have proven to be extremely valuable for a host of climate applications, it is important to understand that the overall quality of reanalysis products varies with latitude, height, time period, spatial and temporal scale, and quantity or variable of interest (Sections 2.1, 2.2, 2.3, and 2.4).
- Current global reanalysis data are most reliable in Northern Hemisphere middle latitudes, in the middle to upper troposphere, and on synoptic (weather) and larger spatial scales. They are least reliable near the surface, in the stratosphere, tropics, and polar regions (Sections 2.2, 2.3, and 2.4).
- Current global reanalysis data are most reliable on daily to interannual time scales. They are least reliable in the representation of the diurnal cycle and in the representation of decadal and longer time scales where they are most impacted by deficiencies in the coverage and quality of observational data and changes in observing systems over time (Sections 2.2, 2.3, 2.4).
- Current global reanalysis data are most reliable in quantities that are most strongly constrained by the observations (*e.g.*, temperature and winds), and least reliable for quantities that are highly model dependent, such as evaporation, precipitation, and cloud-related quantities (Sections 2.2, 2.3, 2.4).

- Substantial biases exist in various components of the atmospheric water cycle (*e.g.*, precipitation, evaporation and clouds), that limit the value of current reanalysis data for assessing the veracity of these quantities in climate models, as well as for practical applications. There are also significant biases in other surface and near-surface quantities related to deficiencies in representing interactions across the land-atmosphere and ocean-atmosphere interfaces (Sections 2.2, 2.3, 2.4).
- The comprehensive and multi-variate nature of reanalysis data provide value for understanding the causes of surface temperature and precipitation trends beyond what can be obtained from relatively incomplete observational datasets alone, even in the face of the noted biases in reanalysis-based trends (Section 2.4).
- Reanalysis data play a critical role in assessing the ability of climate models to simulate the statistics of climate – the means and variances (at various time scales) of basic variables such as the horizontal winds, temperature and pressure. In addition, the adjustments or analysis increments (*i.e.*, the "corrections" imposed on model states by the observations) produced during the course of a reanalysis provide a means to identify fundamental errors in the physical processes and/or missing physics that create climate model biases (Sections 2.2, 2.3).
- Reanalyses have had enormous benefits for climate research and prediction, as well as for a wide range of societal applications. Significant future improvements are possible by developing new methods to address observing system inhomogeneities, by developing estimates of the reanalysis uncertainties, by improving our observational database, and by developing integrated Earth system models and

analysis systems that incorporate key climate elements not included in atmospheric reanalyses to date (Section 2.5).

2.1. WHAT IS A CLIMATE REANALYSIS, AND WHAT ROLE DOES REANALYSIS PLAY WITHIN A COMPREHENSIVE CLIMATE OBSERVING SYSTEM?

2.1.1 Introduction

The world's weather and climate vary continuously on all time scales. The observation and prediction of these variations is vital to many aspects of human society. Extreme weather events can cause significant loss of life and damage to property. Seasonal to interannual changes associated with the El Niño-Southern Oscillation (ENSO) phenomenon and other modes of climate variability have substantial effects on the economy. Climate change, whether natural or anthropogenic, can profoundly influence social and natural environments throughout the world, with consequent impacts that can be large and far-reaching.

Determining the nature and predictability of climate variability and change is crucial to our future welfare. To address the threats and opportunities associated with weather phenomena, an extensive weather observing system has been put in place over the past century. Over the years, considerable resources have been invested in obtaining observations of the ocean, land, cryosphere, and atmosphere from satellite and surface-based systems, with plans to improve and expand these observations as a part of the Global Earth Observing System of Systems (GEOSS, 2005). Within this developing climate observing system, climate analysis plays an essential synthesizing role by integrating together data obtained from this diverse array of Earth system observations to enable improved descriptions and understanding of climate variations and change.

2.1.2 What is a Climate Analysis?

As discussed in Chapter 1, at its most fundamental level, an *analysis* is a detailed representation of the state of the atmosphere (and, more generally, other components of the Earth's climate system, such as oceans or land surface) that is based on observations. A number of techniques can be used to create an analysis from a given set of observations.

One common technique for creating an analysis is based on the expertise of human analysts, who apply their knowledge of phenomena and physical relationships to interpolate values of variables between observation locations. Such subjective analysis methods were almost universally employed before the advent of modern numerical weather prediction in the 1950s and are still used for many purposes today. While such techniques have certain advantages, including the relative simplicity by which they may be produced, they also suffer from key deficiencies that limit their value for numerical weather prediction and much climate research. An important practical deficiency, recognized in the earliest attempts at numerical weather prediction (Richardson, 1922; Charney, 1951), is that the process of creating a detailed analysis, for example, of the global winds, temperatures, and other variables through the depth of the atmosphere on a given day, is quite time consuming, often taking much longer to produce than the evolution of the weather itself. A second, more subtle deficiency is that physical imbalances between fields that are inevitably produced during a subjective analysis lead to forecast changes that are much larger than actually observed (Richardson, 1922). A third limitation of the subjective analysis method is that it is not reproducible. That is, the same analyst, given the same observational data, will generally not produce an identical analysis when given multiple opportunities.

Thus, by the early 1950s the need for an automatic, objective analysis of atmospheric conditions had become apparent. What made this goal feasible was the vital technological advance provided by the early computers of that day which, while quite primitive by today's standards, could still perform calculations far faster than previously possible.

The first objective analyses employed simple statistical techniques to interpolate data values from the locations where observations were made onto uniform spatial grids that were used for the model predictions. Such techniques are still widely employed today to produce many types of analyses, for example, global maps of surface temperatures and precipitation (Jones *et al*., 1999; Hansen *et al*., 2001; Doherty *et al*., 1999; Huffman *et al*., 1997; Xie and Arkin, 1997; Adler *et al*., 2003). However, purely statistical approaches, while of great value, also have limitations. In particular, they do not fully exploit known physical relationships among different variables of the climate system, for example, among fields of temperature, winds, and atmospheric pressure. These relationships place fundamental constraints on how weather and climate evolve in time. For this reason, statistical analysis techniques alone, while highly useful in representing fields of individual variables, are often less well-suited for applications that depend sensitively on relationships among variables, as in numerical weather prediction or in research to assess detailed mechanisms for climate variability and change.

An alternative objective analysis method, and the one that is the principal focus for this Report, is to estimate the state of the climate system (or of one of its components) by combining observations together within a numerical prediction model that represents mathematically the physical and dynamical processes operating within the system. This observations-model integration is achieved through a technique called data assimilation**.** One vital aspect of a comprehensive climate observing system achieved through data assimilation is the ability to integrate diverse surface, upper air, satellite and other observations together into a coherent, internally consistent depiction of the state of the global climate system. Figure 2.1 shows, for example, a snapshot of the coverage provided by the different atmospheric observing systems on 5 September 2003 that can be incorporated into such an analysis scheme.

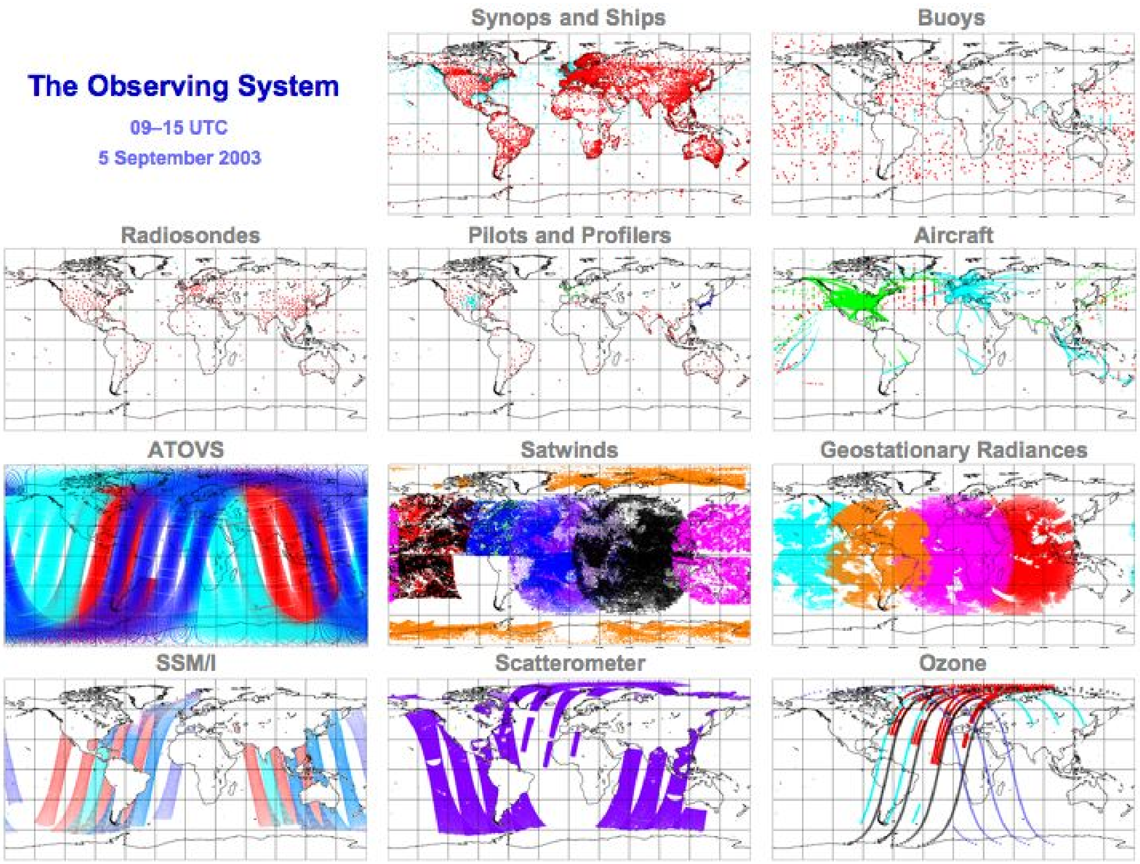

Figure 2.1 An example of the atmospheric data coverage provided by the modern observing systems (5 September 2003) for use in reanalysis. Taken from Simmons (2006).

How do we go about combining observations that have such different spatial coverage, sampling density and error characteristics? The basic method of data assimilation consists of mathematically combining a background field or "first guess" produced by a numerical prediction of the atmosphere (or oceans) with available observations in a way designed to minimize the overall errors in the analysis. Figure 2.2 shows schematically how data assimilation combines quality-controlled observations with a short-term model forecast (typically, a six-hour forecast) to produce an analysis that attempts to minimize errors in estimates of the atmospheric state that would be present from either the observations or model evaluated separately (for more details see Appendix 2.A).

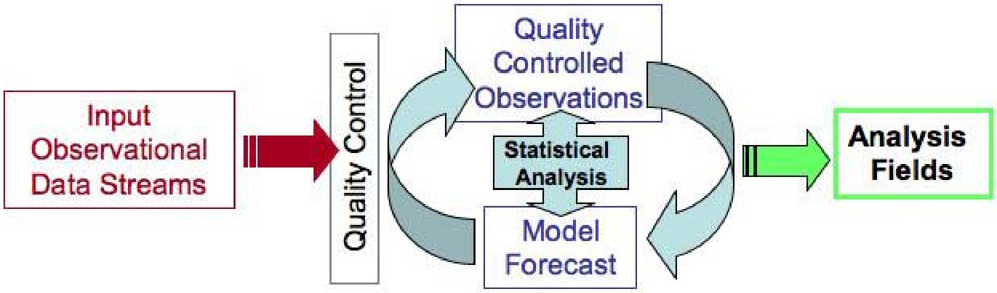

Figure 2.2 A schematic of data assimilation (adapted from a slide from Ricky Rood).

In practice, the quality of a global analysis is impacted by a multitude of practical decisions and compromises, involving the analysis methodology, quality control, the choice of observations and how they are used, and the model (see Appendix 2.A and discussion below). As one illustration of an analysis product, Figure 2.3 compares three different analyses produced from the observations available for 5 September 2003 (Figure 2.1) of the mid-troposphere pressure distribution (the geopotential height field) and total water vapor fields.

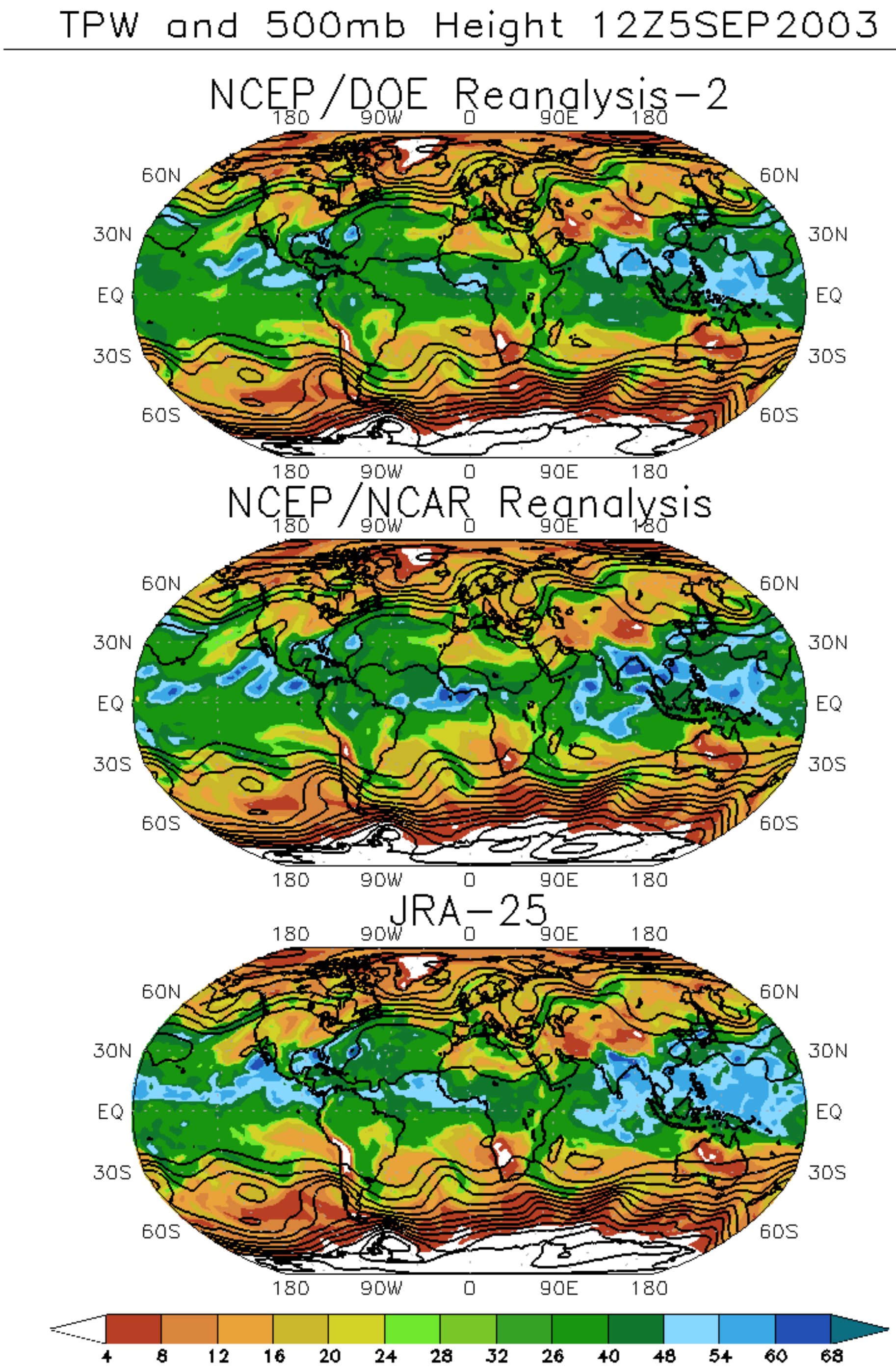

Figure 2.3 An example of the global distribution of the mid-tropospheric pressure field (contours are of the 500mb geopotential height field) and vertically integrated water vapor (shaded color - units are in mm) for 5 September 2003 from three different analyses.

We note that the two NCEP reanalyses were carried out with basically the same system (Table 2.1 – the NCEP/DOE reanalysis system corrected some of the known errors in the NCEP/NCAR system).

Table 2.1 Characteristics of existing atmospheric reanalyses.

Organization	**Time Period**	**AGCM**	**Analysis scheme**	**Output**	**References**
NASA DAO	1980-1994	2X2.5° Lat/lon- $\Delta x \sim 250$ km, L20 (σ, top at 10mb), specified soil moisture	Optimal Interpolation (OI) with incremental analysis update	No longer available	Schubert *et al*. (1993)
NOAA NCEP and NCAR (R1)	1948-present	T62 - $\Delta x \sim 200$km L28 (σ, top at about 3mb)	Spectral Statistical Interpolation (SSI)	http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html	Kalnay *et al* (1996)
NOAA NCEP and DOE (R2)	1979-present	T62 - $\Delta x \sim 200$km L28 (σ, top at about 3mb)	Spectral Statistical Interpolation (SSI)	http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/	Kanamitsu *et al*. (2002) (Fixes errors found in R1 including fixes to PAOBS, snow, humidity, *etc*.)
ECMWF (ERA-15)	1979-1993	T106 - $\Delta x \sim 125$km L31(σ-p, top at 10mb)	Optimal Interpolation (OI),1DVAR, nonlinear normal mode initialization	http://data.ecmwf.int/data/d/era15/	Gibson *et al* (1997)
ECMWF (ERA-40)	1957-2001	T159 - $\Delta x \sim 100$km L60 (σ-p, top at 0.1mb)	3DVAR, radiance assimilation	http://data.ecmwf.int/data/d/era40_daily/	Uppala *et al*. (2005)
JMA and CRIEPI (JRA-25)	1979-2004	T106- $\Delta x \sim 125$km L40 (σ-p, top at 0.4mb)	3D-Var, radiance assimilation	http://jra.kishou.go.jp/index_en.html	Onogi *et al*. (2005)
North American Regional Reanalysis (NARR)	1979-present	$\Delta x = 32$km L45	3D-Var, precipitation assimilation	http://nomads.ncdc.noaa.gov/#narr_datasets	Mesinger *et al*. (2006)

The three analyses show substantial agreement in mid-latitudes, especially for the pressure distribution. There is, however, substantial disagreement in the tropical moisture fields between the NCEP and JRA products. These differences indicate that there are insufficient observations and knowledge of physical processes (as reflected in the models) to tightly constrain the analyses and consequently, the uncertainties in the tropical moisture field are relatively large.

The numerical prediction model used for data assimilation plays a fundamental role in the analysis. It ensures an internal consistency of physical relationships among variables like temperatures, pressure, and wind fields, and provides a detailed, three-dimensional representation of the system state at any given time, including (for the atmosphere) winds, temperatures, pressures, humidity, and numerous other variables that are central for describing weather and climate (Appendix 2.A). Further, the physical relationships among atmospheric (or oceanic) variables that are represented in the mathematical model enable the model to propagate information from times or regions with more observations to other times or areas with sparse observations. At the same time, potential errors are introduced by the use of a model, as discussed in more detail later in this chapter.

Beginning in the 1970s, the sequence of initial atmospheric conditions or analyses needed for the emerging comprehensive global numerical weather prediction models were also used for climate analysis (Blackmon *et al*., 1977; Lau *et al*., 1978; Arkin, 1982). This unforeseen use of the analyses marked what could be considered a revolutionary step forward in climate science, enabling for the first time detailed quantitative analyses that were instrumental in advancing our ability to identify, describe, and understand many large scale climate variations, in particular, some of the major modes of climate variability described later in this chapter. However, the frequent changes in analysis systems needed to improve short-range numerical weather forecasts also introduced spurious shifts in the perceived climate that rendered these initial analyses unsuitable for problems such as detecting subtle climate trends. Recognition of this fundamental issue led to recommendations for the development of a comprehensive, consistent analysis of the climate system, effectively giving birth to the concept of a model-based climate reanalysis (Bengtsson and Shukla, 1988; Trenberth and Olson, 1988).

2.1.3 What is a Climate Reanalysis?

A climate reanalysis is an analysis performed with a fixed numerical prediction model and data assimilation method that assimilates quality-controlled observational data over an extended time period, typically several decades, to create a long-period climate record. This use of a fixed model and data assimilation scheme differs from analyses performed for daily weather prediction. Such analyses are conducted with models with numerical and/or physical formulations as well as data assimilation schemes that are updated frequently, sometimes several times a year, giving rise to “apparent” changes in climate that limit their value for climate applications. Climate analysis also differs fundamentally from weather analysis in that observations throughout the system evolution are available to be used, rather than simply those prior to the time when the forecast is initiated. While weather analysis has the goal of enabling the best short-term weather forecasts, climate analysis can be optimized to achieve other objectives, for example, to provide a consistent description of the atmosphere over an extended time period. However, current climate reanalyses evolved from methods developed for short-range weather prediction, and so have yet to realize their full potential for climate applications (see also Chapter 4).

Beginning in the late 1980s, several reanalysis projects were initiated to develop long time records of analyses better suited for climate purposes (Table 2.1). The products of these first reanalyses have proven to be among the most valuable and widely used in the history of climate science, as indicated both by the number of scholarly publications that rely upon them and by their widespread use in current climate services. They have produced detailed atmospheric climate records that have enabled successful climate monitoring and research to be conducted. They have provided a vitally needed test bed for improving prediction models on all time scales (see next section), especially for seasonal-to-interannual forecasts, as well as greatly improved basic observations and data sets prepared for their production. Reanalysis, when extended to the present as an ongoing climate analysis, provides decision makers with information about current climate events in relation to past events, and contributes directly to climate change assessments.

2.1.4. What Role Does Reanalysis Play within a Climate Observing System?

One of the key limitations of current and foreseeable observing systems is that they do not provide complete spatial coverage of all relevant components of the climate system. In fact, the observing system has evolved over the last half century mainly in response to numerical weather prediction needs, and hence is focused primarily on the atmosphere. This system today consists of a mixture of *in situ* and remotely sensed observations with differing spatial and temporal sampling and error characteristics (Figure 2.1). An example of the observations available for reanalysis during the modern satellite era is provided in Table 2.2.

Table 2.2 An example of the conventional and satellite radiance data available for reanalysis during the satellite era (late 1970s to present). These are the observations used in the new NASA MERRA reanalysis (Section 2.5.2).

DATA SOURCE/TYPE	PERIOD	DATA SUPPLIER
Conventional Data		
Radiosondes	1970 - present	NOAA/NCEP
PIBAL winds	1970 - present	NOAA/NCEP
Wind profiles	1992/5/14 - present	UCAR CDAS
Conventional, ASDAR, and MDCRS aircraft reports	1970 - present	NOAA/NCEP
Dropsondes	1970 - present	NOAA/NCEP
PAOB	1978 - present	NCEP CDAS
GMS, METEOSAT, cloud drift IR and visible winds	1977 Š present	NOAA/NCEP
GOES cloud drift winds	1997 Š present	NOAA/NCEP
EOS/Terra/MODIS winds	2002/7/01 - present	NOAA/NCEP
EOS/Aqua/MODIS winds	2003/9/01 - present	NOAA/NCEP
Surface land observations	1970 - present	NOAA/NCEP
Surface ship and buoy observations	1977 - present	NOAA/NCEP
SSM/I rain rate	1987/7 - present	NASA/GSFC
SSM/I V6 wind speed	1987/7 - present	RSS
TMI rain rate	1997/12 - present	NASA/GSFC
QuikSCAT surface winds	1999/7 - present	JPL
ERS-1 surface winds	1991/8/5 Š 1996/5/21	CERSAT
ERS-2 surface winds	1996/3/19 Š 2001/1/17	CERSAT
Satellite Data		
TOVS (TIROS N, N-6, N-7, N-8)	1978/10/30 Š 1985/01/01	NCAR
(A)TOVS (N-9; N-10 ; N-11; N-12)	1985/01/01 - 1997/07/14	NOAA/NESDIS & NCAR
ATOVS (N-14; N-15; N-16; N-18; N-18)	1995/01/19 - present	NOAA/NESDIS
EOS/Aqua	2002/10 - present	NOAA/NESDIS
SSM/I V6 (F08, F10, F11, F13, F14, F15)	1987/7 - present	RSS
GOES sounder T_B	2001/01 - present	NOAA/NCEP
SBUV2 ozone (Version 8 retrievals)	1978/10 - present	NASA/GSFC/Code 613.3

A major strength of modern data assimilation methods lies in the use of a model to help fill in the gaps of our observing system. This can be considered as a very sophisticated interpolator that uses the complex equations governing the atmosphere's evolution together with all available observations to estimate the state of the atmosphere in regions with little or no observational coverage. Statistical schemes are employed that ensure that, in the absence of bias with respect to the true state of the atmosphere, the observations and model first guess are combined in an optimal way to jointly minimize observational and model errors, subject to certain simplifying assumptions such as normality of the statistics. This can be as simple as the model transporting warm air from a region that has good observational coverage (say over the United States) to a region that has little or no coverage (say over the adjacent ocean), or a more complicated "extrapolation", for example, where the model generates a realistic low-level jet in a region where such phenomena exist but observations are limited. The latter is an example of a phenomenon that is largely generated by the model, and only indirectly constrained by observations. This example highlights both the tremendous advantages and difficulties in using reanalysis for climate studies since it allows us, through a model (which is imperfect), to "observe" features that are indirectly or incompletely measured.

The use of a model also enables estimates of quantities and physical processes that are very difficult to observe directly, such as vertical motions, surface heat fluxes, latent heating, and many of the other physical processes that determine how the atmosphere evolves in time. Such quantities are in general highly model dependent and great care must be used in interpreting them. Any bias in the model fields or incorrect representation of physical processes (called parameterizations) will be reflected in the reanalysis to some extent. In fact, only recently have the models become good enough to be used with some confidence in individual physical processes. Until recently, most studies using assimilated data have taken an indirect approach to estimating physical processes by computing them as a residual of a budget that involves only variables that are well observed (see Section 3.2.3). Thus it is important to have a good understanding of which quantities are strongly constrained by the observations, and which are only indirectly constrained and depend critically on model parameterizations. In recognition of this problem, efforts have been made to document the quality of the individual products and categorize them according to how strongly they are observationally constrained (*e.g.*, Kalnay *et al*., 1996; Kistler *et al*., 2001).

Beyond their fundamental integrating role within a comprehensive climate observing system, climate analysis and reanalysis can also be used to identify redundancies and gaps in the climate observing system, thus enabling the entire system to be configured more cost effectively. By directly linking products to observations, a reanalysis can be applied in conjunction with other science methods to optimize the design and efficiency of future climate observing systems and to improve the products that the system produces.

Despite the usefulness of current reanalysis products, they also suffer from significant limitations. For example, they are affected by changes in the observing systems, such as the introduction of satellite data in 1979, and other newer remote sensing instruments (Figure 2.4). Such changes to the observing system strongly affect the variability that is inferred from reanalyses. In particular, inferred trends and low frequency variability are of limited reliability, a result exacerbated by model bias (*e.g.*, Figure 2.5 and discussion in Sections 2.3.2.2 and 2.4.2).

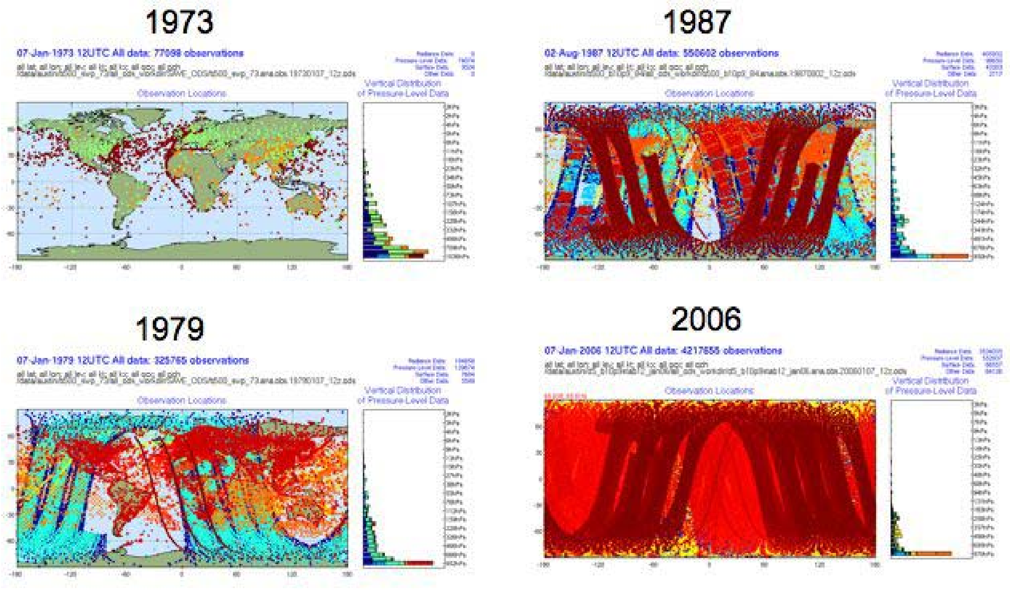

Figure 2.4 Changes in the distribution and number of observations available for NASA's MERRA reanalysis.

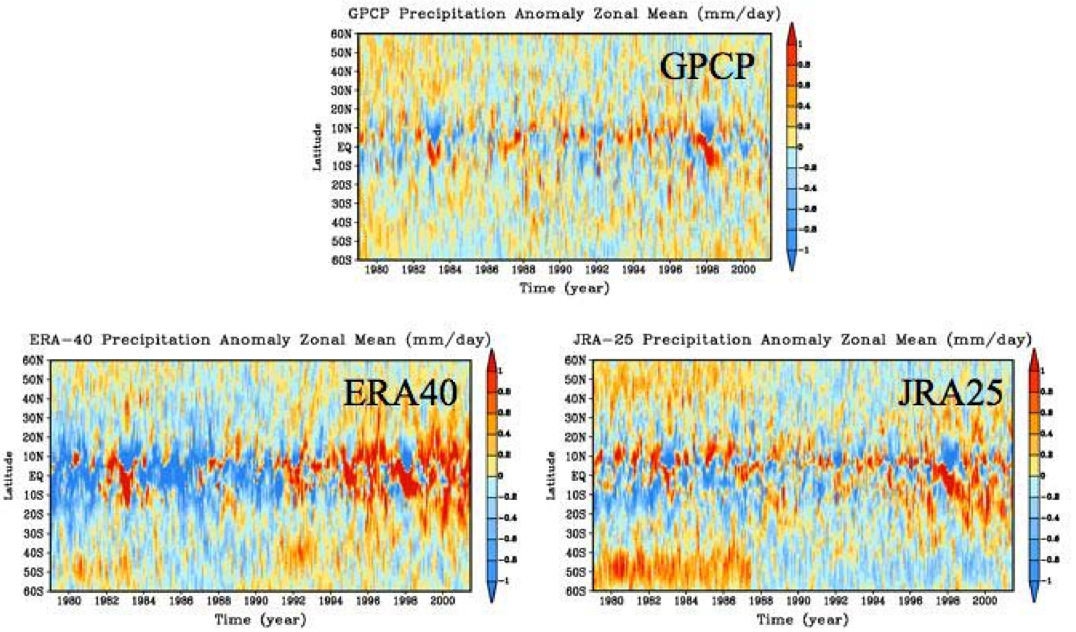

Figure 2.5 Trends and shifts in the reanalyses. The figures show the zonal mean precipitation from the GPCP observations (top panel), the ERA-40 reanalysis (bottom left panel), and the JRA-25 reanalysis (bottom right panel). Courtesy Junye Chen and Michael Bosilovich, NASA/GMAO.

The need to periodically update the climate record to provide improved reanalyses for climate research and applications has been strongly emphasized (*e.g.*, Trenberth *et al.*, 2002b; Bengtsson *et al.*, 2004a). Some reasons for updating reanalyses are: 1) to include critical or extensive additional observations missed in earlier analyses; 2) to correct erroneous observational data identified through subsequent quality-control efforts; and 3) to take advantage of scientific advances in models and data assimilation techniques, including bias correction techniques (Dee, 2005), and assimilating new types of observations, *e.g.*, satellite data not assimilated in earlier analyses. In the following sections, we discuss strengths and limitations of current reanalyses for addressing specific questions defined in the preface to this Report.

2.2. WHAT CAN REANALYSIS TELL US ABOUT CLIMATE FORCING AND THE VERACITY OF CLIMATE MODELS?

2.2.1 Introduction

Global atmospheric data assimilation combines various observations of the atmosphere (Figure 2.1) with a short-term model forecast to produce an improved estimate of the state of the atmosphere. The model used in the assimilation incorporates our understanding of how the atmosphere (and more generally the climate system) behaves and, ideally, can forecast or simulate all aspects of the atmosphere at all locations around the world.

As such, one can think about atmospheric data assimilation and reanalysis in particular, as a model simulation of past atmospheric behavior that is continually updated or adjusted by available observations. Such adjustments are necessary because the model would deviate from the "path" that nature took because the model is imperfect (our understanding about how the atmosphere behaves and our ability to represent that behavior in computer models is limited), and the information (observations) that we use to correct the model's "path" are incomplete and also contain errors. That is, we don't measure all aspects of the climate system perfectly – if we did, we wouldn't need to do data assimilation!

The above model-centric view of data assimilation is useful when trying to understand how reanalysis data can be applied to tell us about the veracity of climate models. It highlights the fact that reanalysis products are a mixture of observations and model forecasts, and their quality will therefore be impacted by the quality of the model. In large geographic regions with little observational coverage, a reanalysis will tend to reflect the climate of the model. Also, quantities that are poorly observed, such as surface evaporation, depend very much on the quality of the model's representation or parameterizations of the relevant physical processes (*e.g.*, in this case the model's land surface and cloud schemes). Given that models are an integral component of reanalysis systems, how then can we use reanalyses to help us understand errors in our climate models - in some cases the same model used to produce the reanalysis?

2.2.2 Assessing Systematic Errors

The most straightforward approach is simply to compare the basic reanalysis fields (*e.g.*, winds, temperature, moisture) with those that the model produces in free-running mode (a simulation that does not have the benefit of being corrected by the observations)[1]. The results of such comparisons, for example of monthly or seasonal mean values, can indicate whether the model has systematic errors such as being too cold or too wet in certain regions.

In general, such comparisons are only useful for regions and for quantities where the uncertainties in the reanalysis products are small compared to the model errors. For example, if the difference in the tropical moisture field between two reanalysis products (say NCEP/NCAR R1 and ERA-40) is as large as (or larger than) the differences between any one reanalysis product and the model results, then we could not reach any conclusion

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[1] These are typically multi-year AGCM runs started from arbitrary initial conditions and forced by the observed record of sea surface temperatures (SST).

about the model quality based on that comparison. This points to the need for obtaining reliable uncertainty and bias estimates of all reanalysis quantities (*e.g.*, Dee and Todling, 2000) – something that has yet to be achieved in the current generation of reanalysis efforts. In the absence of such estimates, we can (as in the example above) get some guidance on uncertainties and model dependence by simply comparing the available reanalysis data sets. Such comparisons with reanalysis data are now routine and critical aspects of any model development and evaluation effort. Examples of such efforts span the climate modeling community and include the Atmospheric Model Intercomparison Project (AMIP) (Gates, 1992), the tropospheric-stratospheric GCM-Reality Intercomparison Project for SPARC (GRIPS) (Pawson *et al.*, 2000), and coupled model evaluation conducted for the IPCC Fourth Assessment Report (IPCC, 2007).

Figure 2.6 illustrates a simple comparison between various atmospheric models and the first ECMWF reanalysis (ERA-15, see Table 2.1).

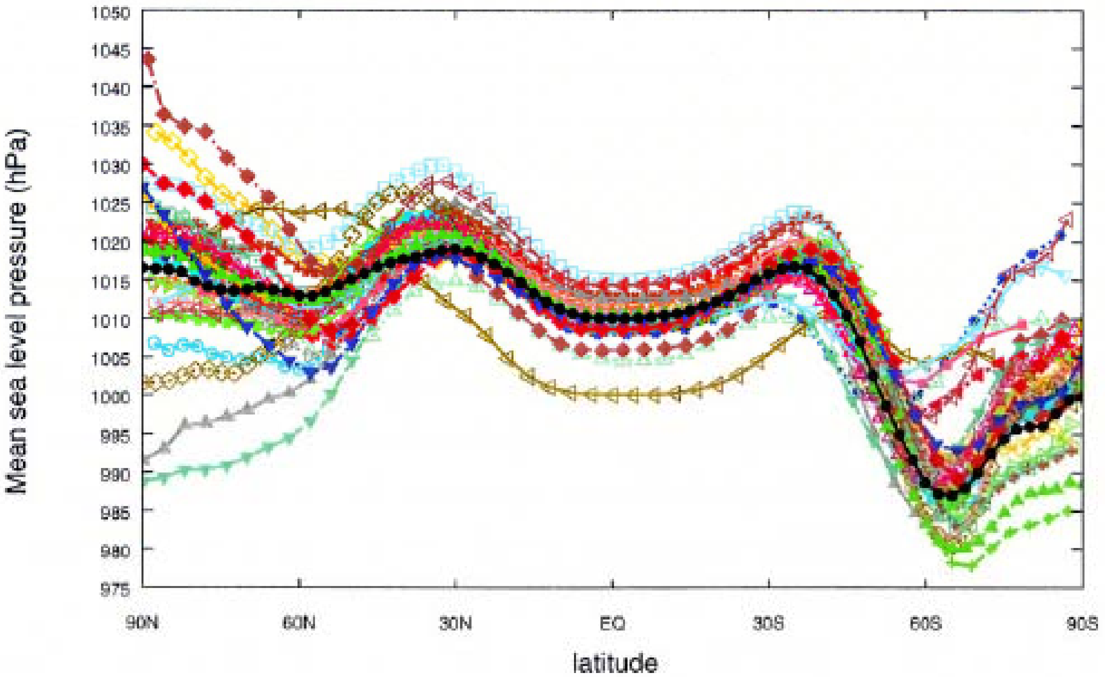

Figure 2.6 The zonal distribution of zonally-averaged sea level pressure simulated by the various AMIP models for DJF of 1979 to 1988 compared against the ECMWF (ERA-15) reanalysis (the black dots; Gibson *et al*. 1997). Taken from Gates *et al*. 1999.

The comparison shows considerable differences among the models in the zonal mean surface pressure, especially at high latitudes. It is interesting that the values scatter around the estimate provided by the reanalysis. Figure 2.7 shows an example of a more in-depth evaluation of the ability of AGCM simulations forced by observed sea surface temperatures to reproduce that part of the variability associated with ENSO.

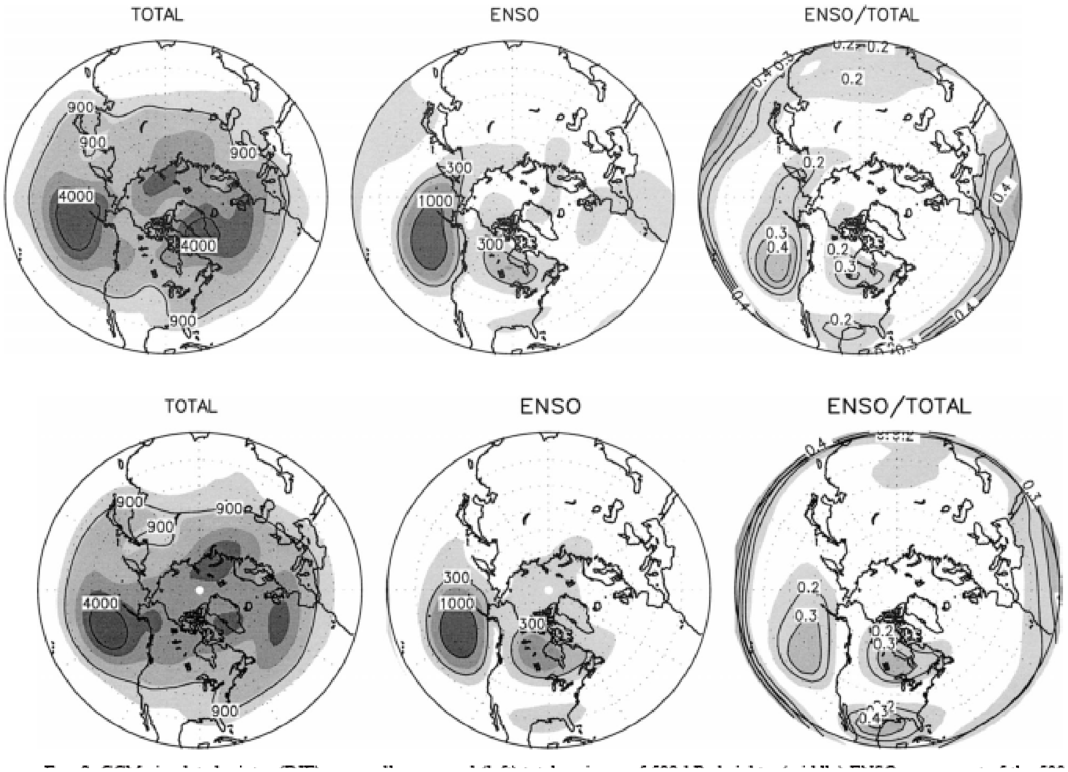

Figure 2.7 The left panels show the total variance of the time mean winter (December, January, February) 500mb height fields. The middle panels show that part of the total variance that is due to ENSO. The right panels show the ratio of the two variances (ENSO/Total). The top panels are from a reanalysis and the bottom panels are from GCM simulations forced with observed sea surface temperatures. The results are computed for the period 1950 to 1999, and plotted for the Northern Hemisphere polar cap to 20°N. The contour interval is 1000 (m^2) in the left and middle panels, and 0.1 in the right panels (taken from Hoerling and Kumar 2002).

In this case the comparison is made with the NCEP/NCAR R1 reanalysis for the winters (DJF) of 1950-1999. The comparison suggests that the models produce a very reasonable response to the ENSO-related sea surface temperature variations.

2.2.3 Inferences about Climate Forcing

While the above comparisons address errors in the description of the climate system, a more challenging problem is to address errors in the forcing or physical mechanisms (in particular the parameterizations) by which the model produces and maintains climate anomalies. This involves quantities that are generally only weakly or indirectly constrained by observations (*e.g.*, Kalnay *et al*., 1996; Kistler *et al*., 2001). Ruiz-Barradas and Nigam (2005) for example, are able to show that land/atmosphere interactions may be too efficient (make too large a contribution) in maintaining precipitation anomalies in the United States Great Plains in current climate models, despite rather substantial differences in the reanalyses. Nigam and Ruiz-Barradas (2006) highlight some of the difficulties that are encountered when trying to validate models in the presence of large differences between the reanalyses in the various components of the hydrological cycle (*e.g.*, precipitation and evaporation). This problem can be alleviated to some extent by taking an indirect approach to estimating the physical processes. In this case, a budget is computed in such a way that the reanalysis quantities that are highly model-dependent are determined indirectly as a residual of terms that are more strongly constrained by the observations (*e.g.*, Sardeshmukh, 1993). Nigam *et al*. (2000) show, for example, that the heating obtained from a residual approach appears to be of sufficient quality to diagnose errors in the ENSO-heating distribution in a climate model simulation.

Another approach to addressing errors in the forcing is to focus directly on the adjustments made to the model forecast during the assimilation (*e.g.*, Schubert and Chang, 1996; Jeuken *et al*., 1996; Rodwell and Palmer, 2007). These corrections can potentially provide a wealth of information about model deficiencies. Typically, the biases seen in, for example, the monthly mean temperature field, are the result of complex interactions among small errors in different components of the model that grow over time. The challenge to modelers is to disentangle the potential sources of error, and ultimately to correct the deficiencies at the process level to improve long-term model behavior.

An important aspect of the corrections made during data assimilation is that they are applied frequently (typically every six hours) so that the impact of the adjustments can be seen before they can interact with the full suite of model processes. In other words, the corrections made during the course of data assimilation give a potentially direct method for identifying errors in the physical processes that create model biases (*e.g.*, Klinker and Sardeshmukh, 1992; Schubert and Chang, 1996; Kaas *et al*., 1999, Danforth *et al*., 2007; Rodwell and Palmer, 2007). In fact, they can also give insights into missing model physics such as dust-forced heating in the lower atmosphere (Alpert *et al*., 1998), radiative heating in the stratosphere from volcanic eruptions (Andersen *et al*., 2001), and impacts of land use changes (Kalnay and Cai, 2003)– processes not represented in the models used in the first generation of reanalyses.

The development of a data assimilation system that provides unbiased estimates of the various physical processes inherent in the climate system (*e.g.*, precipitation, evaporation, cloud formation) is an important step in our efforts to explain, or attribute (see Chapter 3) the causes of climate anomalies. As such, reanalyses allow us to go beyond merely documenting what happened. We can, for example, examine the processes that maintain a large precipitation deficit in some region. Is the deficit maintained by local evaporative processes or changes in the storm tracks that bring moisture to that region, or some combination? As described in the next chapter, reanalysis data provide the first steps in a process of attribution that involves detection and description of the anomalies, and an assessment of the important physical processes that contribute to their development. Ultimately, we seek answers to questions about the causes that cannot be addressed by reanalysis data alone. Going back to the previous example, how can we disentangle the role of local evaporative changes and changes in the storm tracks? This requires model experimentation such as that described in the next chapter. It should be noted that even in that case, reanalyses play an important role in validating the model behavior.

2.2.4 Outlook

There are a number of steps that can be taken to increase the value of reanalyses for identifying model deficiencies, including: improving our estimates of uncertainties in all reanalysis products, balancing budgets of key quantities (*e.g.*, heat, water vapor, energy) (Kanamitsu and Saha, 1996; see also the next section), and reducing the spurious model response to the adjustments made to the background forecast by the insertion of observations (the so-called model spin-up or spin-down problem), especially when the adjustments involve water vapor and the various components of the hydrological cycle (Kanamitsu and Saha, 1996; Schubert and Chang, 1996; Jeuken *et al*., 1996). For example, Annan *et al*. (2005) proposed a method based on an ensemble of roughly 50 forecast integrations that estimates frictional and diffusive parameters. These and other approaches hold substantial promise of obtaining optimal estimates of uncertain model parameters from reanalyses, even for the very complex current climate models.

2.3. WHAT IS THE CAPACITY OF CURRENT REANALYSES TO HELP US IDENTIFY AND UNDERSTAND MAJOR SEASONAL-TO-DECADAL CLIMATE VARIATIONS, INCLUDING CHANGES IN THE FREQUENCY AND INTENSITY OF CLIMATE EXTREMES SUCH AS DROUGHTS?

In this section we examine the strengths and weaknesses of current reanalyses for identifying and understanding climate variability. This is an important step for addressing the more general issue of attribution (how well we understand the causes of climate variability) introduced in Chapter 1 and addressed more fully in Chapter 3. Understanding the connections between reanalysis, models and attribution is crucial for understanding the broader path towards attribution outlined in Chapter 1 (Box 2.1).

Box 2.1 The Complementary Roles of Reanalysis and Free-Running Model Simulations in the Attribution Problem

Section 2.3 demonstrates the value of reanalysis for identifying and understanding climate variability. By providing best estimates of the circulation patterns and other weather elements (moisture transport, evaporation, precipitation and cloudiness) present during observed extremes -- estimates that are temporally and spatially comprehensive and self-consistent -- reanalysis indeed offers a unique and profound contribution to the more general problem of attribution discussed in Chapter 3. Reanalysis is best positioned, for example, to provide a global picture of the prevailing anomalous circulation patterns associated with a given drought. By studying reanalysis data, investigators can hypothesize linkages between the drought and contemporaneous climate anomalies in other parts of the world (*e.g.*, anomalies in sea surface temperatures, or SSTs).

Reanalysis, however, is but one tool for addressing the problem. A drawback of reanalysis in this context is its inability to isolate causality -- to demonstrate unequivocally that one climate feature (*e.g.*, anomalous SSTs) causes another (*e.g.*, drought). Indeed, this drawback would extend to any imaginable set of direct observations of the atmosphere. To isolate causality, we need climate model simulations that are unconstrained by the assimilation of observational data. Such climate models can be forced in different ways to determine whether a certain forcing will cause the model to reproduce a climate anomaly of interest. For example, if an investigator suspects, perhaps based on an analysis of reanalysis data, that anomalous SSTs caused the severe drought in the southern Great Plains during the1950s, he or she could perform two simulations with a free-running climate model, one in which the 1950s SST anomalies are imposed, and one in which they are not. If only the first simulation reproduces the drought, the investigator has evidence to support the hypothesized role of the SSTs. An additional step would be to determine what caused the SST anomalies in the first place, and for that one would need further experiments with a fully coupled atmosphere/ocean/land model.

Such free-running modeling studies, of course, have their own basic deficiencies, most importantly the potential lack of realism in the climate processes simulated by an unconstrained (non-reanalysis) modeling system. This suggests an important additional role of reanalysis in the attribution problem. Not only can the reanalysis data help in the formulation of hypotheses to be tested with a free-running climate model, but the reanalysis data can (and should) be used to verify that the free-running model is behaving realistically, *i.e.*, that the variations in circulation and other climate processes in the free-running model are consistent (statistically and/or mechanistically) with what we have learned from reanalysis (see section 2.2). In effect, reanalysis and free-running model simulations are complementary tools for addressing the attribution problem, each with their own strengths and weaknesses. Only the unconstrained parts of a model can be used to address attribution (causality), implying the need for free-running models, but those unconstrained parts must be evaluated for realism, implying the need for reanalysis. Arguably, the best attack on the attribution problem is to use the reanalysis and free-running model approaches in tandem.

2.3.1. Climate Variability

The climate system varies on a wide range of time and space scales. The variability of the atmosphere in particular encompasses individual weather events that we experience every day, and longer-term changes that affect global weather patterns and can result in regional droughts or wet periods (pluvials) lasting many years. A primary goal of climate research is to understand the causes of these long-term climate variations and changes and to develop models that allow us to predict them.

On intra-seasonal to decadal time scales there are a number of key recurring global-scale patterns of climate variability that have pronounced impacts on the North American climate (Table 2.3). These include the Pacific North American pattern (PNA), the Madden-Julian Oscillation (MJO), the North Atlantic Oscillation (NAO) and the related Northern Annular Mode (NAM), the Quasi-Biennial Oscillation (QBO), El Nino-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multi-decadal Oscillation (AMO). These patterns, sometimes referred to as modes of climate variability or teleconnection patterns, can have pronounced effects on North American climate by shifting weather patterns and disrupting local climate features (*e.g.*, Gutzler *et al*., 1988; Hurrell, 1996).

Table 2.3 Characteristics of some of the leading modes of climate variability that are known to have a substantial impact on North American climate. The last column provides a subjective assessment of the quality of the atmospheric manifestations of these modes (and their impacts on regional climate) in current atmospheric reanalyses.

Phenomena	**Key references**	**Time scales**	**Link between atmosphere and ocean**	**Some impacts on North America**	**Consistency between atmospheric reanalyses**
Pacific/North American (PNA) pattern	Wallace and Gutzler (1981)	Subseasonal to Seasonal	Weak to moderate	West coast storms	good
Madden Julian Oscillation (MJO)	Madden and Julian (1994)	Approximately 30-60 days	Weak to moderate	Atlantic hurricanes	Fair to poor
North Atlantic Oscillation (NAO)	Hurrell *et al.* (2001)	Subseasonal to decadal	moderate on long time scales	East coast winters	good
Northern Annular Mode (NAM)	Thompson (2000);	Subseasonal to decadal	moderate on long time scales	East coast winters	Good to fair in stratosphere

	Wallace (2000)				
El Nino/ Southern Oscillation (ENSO)	Philander (1990)	Seasonal to interannual	strong	Winter in west coast and southern tier of United States, Mexico, warm season regional droughts	Good to fair on longer time scales
Pacific Decadal Oscillation (PDO)	Zhang *et al.* (1997)	decadal	strong	Drought or pluvials over North America	Fair to poor
Atlantic Multi-decadal Oscillation (AMO)	Folland *et al.* (1986)	decadal	strong	Drought or pluvials over North America, Atlantic hurricanes	Fair to poor

As we shall see in the following sections, the quality of the representation of these phenomena in reanalyses vary and depend on the time scales, locations, and physical mechanisms relevant to each of these modes of variability. The last column in Table 2.3 gives our expert assessment of the consistency of the atmospheric manifestations of these modes (and their impacts on regional climate) in current reanalyses based on such general considerations.

Figures 2.8 and 2.9 show examples of the connection between the PNA and NAO patterns and North American surface temperature and precipitation variations. The spatial correspondence between the reanalysis tropospheric circulation and the independently-derived surface fields show the potential value of the reanalysis data for interpreting the relationships between changes in the climate modes and regional changes in surface temperature and precipitation.

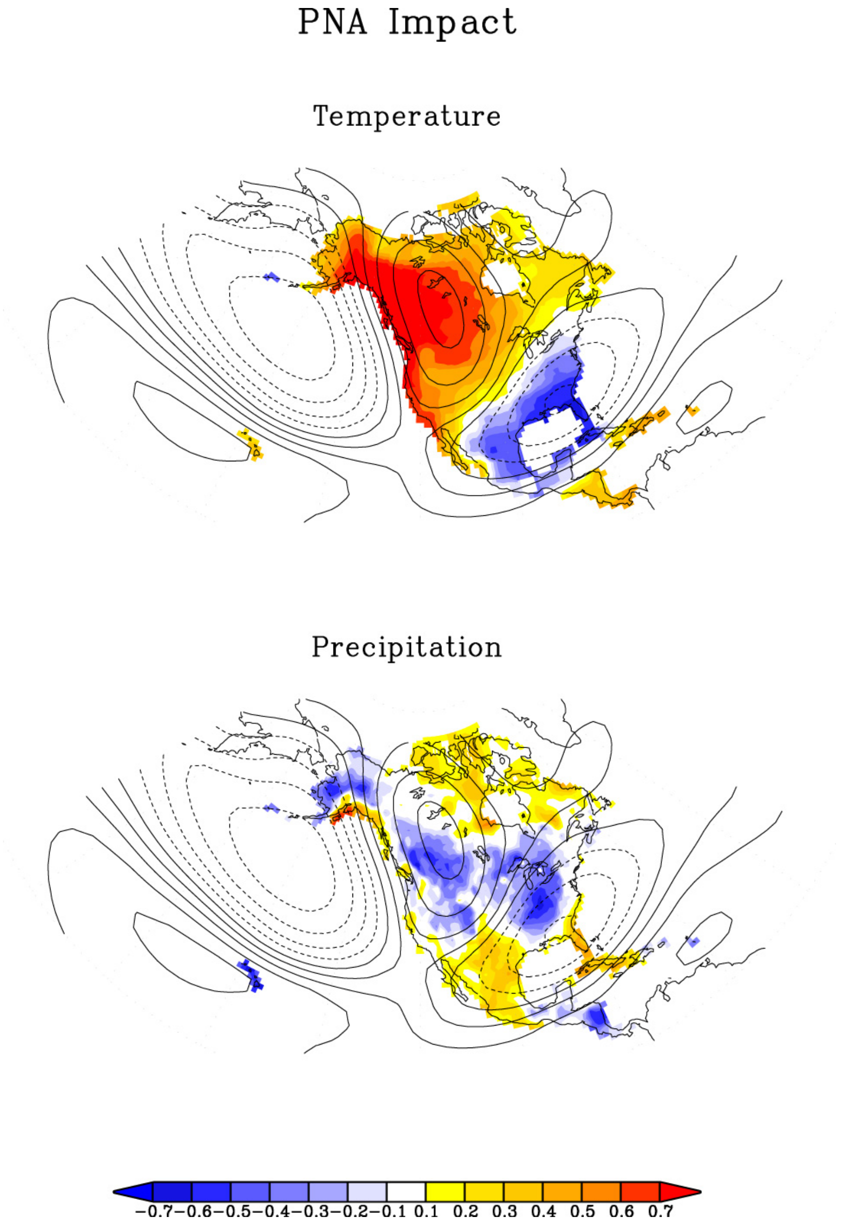

Figure 2.8 The correlation between the PNA index (Wallace and Gutzler 1981) and 500mb height field (contours). The shading indicates the correlations between PNA index and a) the surface temperature and b) the precipitation. The 500mb height is from the NCEP/NCAR R1 reanalysis. The surface temperature and precipitation are from independent observational data sets. The correlations are based on seasonal mean data for the period 1951 to 2006. The contours of correlation give an indication of the direction of the mid-tropospheric winds, and the positions of the troughs and ridges.

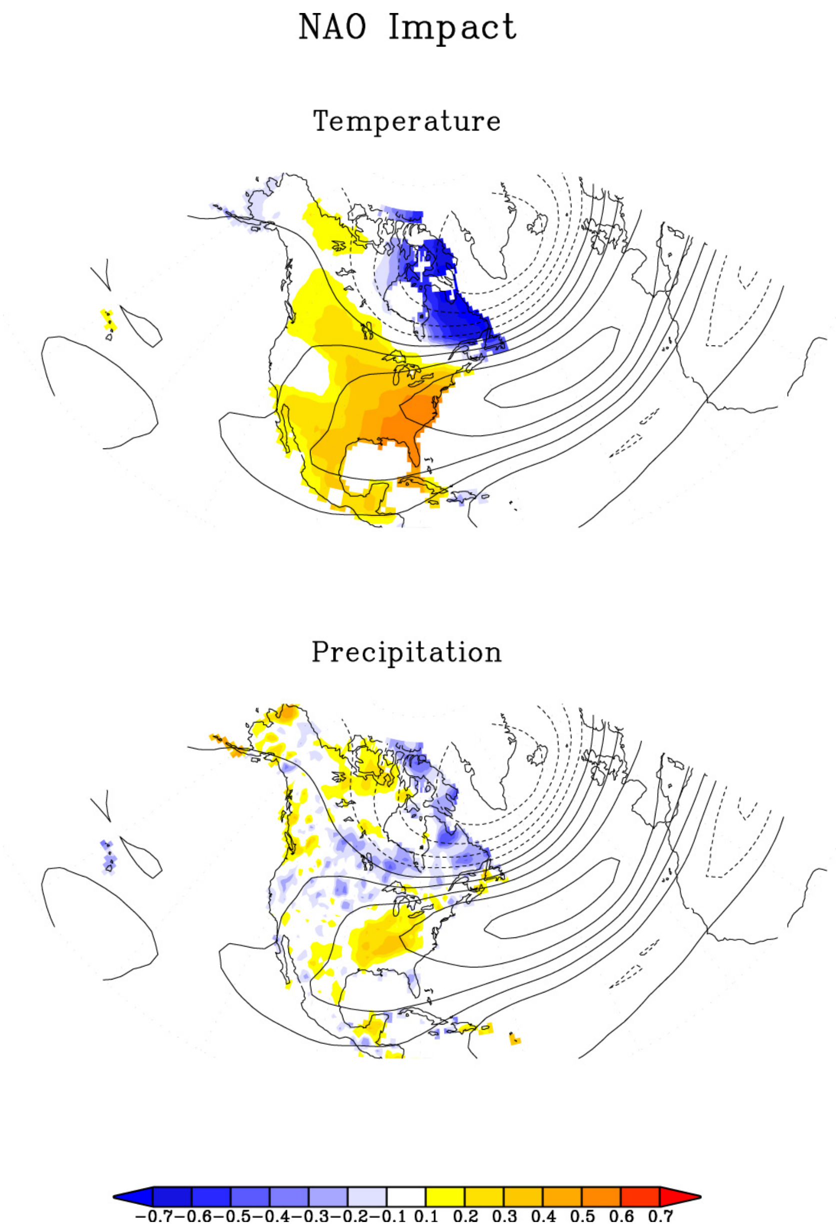

Figure 2.9 The correlation between the NAO index (Wallace and Gutzler 1981) and 500mb height field (contours). The shading indicates the correlations between NAO index and a) the surface temperature and b) the precipitation. The 500mb height is from the NCEP/NCAR R1 reanalysis. The surface temperature and precipitation are from independent observational data sets. The correlations are based on seasonal mean data for the period 1951 to 2006. The contours of correlation give an indication of the direction of the mid-tropospheric winds, and the positions of the troughs and ridges.

Specifically, during the positive phase of the PNA pattern, surface temperatures over western North America tend to be above average, and this can be related to an unusually strong high pressure ridge over the region as well as transport of warm Pacific air poleward along the west coast extending to Alaska. An upper-level trough centered over the southeast United States and the associated intensified north to south flow over the center of the continent facilitates the southward transport of Arctic air that produces a tendency toward below normal temperatures over the Gulf coast states. This same flow pattern is associated with transport of relatively dry polar air and a tendency to produce descending motions in the middle troposphere over the Missouri and Mississippi regions, both of which favor below normal precipitation, as observed. In contrast, the positive phase of the NAO pattern is accompanied by above average temperatures over the eastern United States and wetness in the Ohio Valley. The reanalysis data of tropospheric circulation help to interpret this relationship as resulting from a northward shifted westerly flow regime over the eastern United States and North Atlantic that inhibits cold air excursions while simultaneously facilitating increased moisture convergence into the region .

The above patterns arise mainly, but not exclusively, as manifestations of internal atmospheric variability (*e.g.*, Massacand and Davies, 2001; Cash and Lee, 2001; Feldstein, 2002, 2003; Straus and Shukla, 2002), and as discussed in Chapter 3, are also linked in varying degree to land surface and ocean variations. Understanding seasonal to decadal climate variability requires that we understand the physical mechanisms that produce these large-scale patterns, including how they interact with each other, and their coupling with the different climate system components (Chapter 3).

A key factor that limits our ability to fully understand such long-term variability has been the lack of long-term comprehensive and consistent observations of the climate system, including observations of the land and ocean, which are critical to understanding and predicting atmospheric variability on seasonal and longer time scales. Observations of each of these components of the climate system, while improving with the advent of the satellite era, are still far from satisfactory for addressing climate problems. In order to adequately address seasonal and longer variability, the observations need to cover many decades, span the globe, include all the key climate parameters, be consistent with our best physical understanding, and be continuous in time.

While these conditions are not fully met for any components of the climate system (see the following sections), the most advanced observational capabilities are of the atmospheric component. This system was developed primarily to support weather prediction, with major advances occurring with the advent of an upper air network of radiosondes in the 1950s, and with a near global observing system provided by the great increases in satellite measurements beginning in the late 1970s. While new efforts are underway to develop a true climate observing system spanning all climate system components and that provides continuity in time and space, the present climate observing system is inadequate for many applications (GEOSS, 2005).

2.3.2 Reanalysis and Climate Variability

One of the most important insights of the last few decades regarding our existing observational record was that we could leverage our investment in operational weather prediction by harnessing the prediction infrastructure (the global models and data assimilation methods for combining disparate observations) to develop a more consistent historical record of the atmosphere (Bengtsson and Shukla, 1988; Trenberth and Olson, 1988). This led to the development of several atmospheric climate reanalysis data sets (Schubert *et al.*, 1993; Kalnay *et al.*, 1996; Gibson *et al.*, 1997). These data sets provided the first comprehensive depictions of the global atmosphere that, in the case of the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) now span over 60 years. Studies using these and several follow-on reanalyses (Kanamitsu *et al.*, 2002; Uppala *et al.*, 2005; Onogi *et al.*, 2005; Mesinger *et al.*, 2006[2]) to examine seasonal to decadal variability of climate form the basis for this section (Table 2.1).

Over extended time periods, the reanalysis data provide the most comprehensive picture to date of the state of the atmosphere and its evolution. The reanalyses also provide estimates of the various physical processes such as precipitation, cloud formation, and radiative fluxes that are required to understand the mechanisms by which climate evolves. As we examine the utility of current reanalyses for identifying and understanding atmospheric variability, the critical roles of the model in determining the quality of the reanalysis must be recognized, and the impact of the spatial and temporal inhomogeneities of the observing system must also be appreciated. When assessing the utility of the reanalyses, we must also consider the nature of the problem that is being addressed. What is the time scale? What is the spatial scale? Does the problem involve the tropics or Southern Hemisphere, which tend to be less well observed, especially before the advent of satellite observations? To what extent are water vapor and clouds, or

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[2] While not global, the North American Regional Reanalysis (NARR) has played an important role for studying regional climate variability. Two of its key strengths are the enhanced resolution, and the fact that precipitation observations were assimilated.

links to the land surface or the ocean important? These are important considerations, because assimilation systems used for the first generation of reanalyses evolved out of the needs of numerical weather prediction, which did not place a high priority on modeling details of the hydrological cycle or links to the land and ocean, which were deemed to be of secondary importance for producing weather forecasts from a day to a week in advance.

In the following subsections, we address the capacity of current reanalyses to describe and understand major seasonal-to-decadal climate variations by examining three key aspects of reanalyses: their spatial characteristics, their temporal characteristics, and their internal consistency and scope. We include in each subsection key examples of where reanalyses have contributed to our understanding of seasonal to decadal variability and where they fall short. We build on the results of two major international workshops on reanalysis (WCRP, 1997; WCRP, 1999) by emphasizing studies that have appeared in the published literature since the last workshop.

2.3.2.1 Spatial characteristics

The globally complete spatial coverage provided by reanalyses, along with estimates of the physical processes that drive the atmosphere, has greatly facilitated diagnostic studies that attempt to identify the causes of large-scale atmospheric variability that have substantial impacts on North American weather and climate (*e.g.*, the NAO and PNA). Our understanding of the nature of both the NAO and PNA has been substantially improved by studies using reanalysis products. Thompson and Wallace (2000), for example, provided a global perspective on the NAO, using reanalysis data to link it to the so-called Northern Hemisphere Annular Mode (NAM), and noting the similarities of that mode to another annular mode in the Southern Hemisphere. Reanalysis data have also been used to link the variability of the NAO to that in the stratosphere in the sense that anomalies developing in the stratosphere propagate into the troposphere, suggesting an intriguing source of potential predictability on intraseasonal time scales (*e.g.*, Baldwin and Dunkerton, 1999; 2001). Detailed studies made possible by reanalysis data have contributed to our understanding that both PNA and NAO modes of variability are fundamentally internal to the atmosphere, that is, they would exist naturally in the atmosphere without any anthropogenic or other "external" forcing (*e.g.*, Massacand and Davies, 2001; Cash and Lee, 2001; Feldstein, 2002; 2003; Straus and Shukla, 2002; see also next chapter on attribution). Straus and Shukla (2002), in particular, emphasized the differences between the PNA and a similar pattern of variability in the Pacific/North American region that is forced primarily as an atmospheric response to the tropical sea-surface temperature changes associated with ENSO.

In addition to improving our understanding of various global modes of atmospheric variability, reanalysis data allow in-depth evaluations of the physical mechanisms and global connections of high impact regional climate anomalies such as droughts or floods. For example, Mo *et al*. (1997), building on several earlier studies (*e.g.*, Trenberth and Branstator, 1992; Trenberth and Guillemot, 1996), capitalized on the long record of the NCEP/NCAR global reanalyses to provide a detailed analysis of the atmospheric processes linked to floods and droughts over the central United States, including precursor events tied to large-scale wave propagation and changes in the Great Plains low level jet (LLJ). Liu *et al*. (1998) use reanalysis data in conjunction with a linear model to deduce the role of various physical and dynamical processes in the maintenance of the circulation anomalies associated with the 1988 drought and 1993 flood over the United States.

Process studies focused on North America have benefited from the high resolution and improved precipitation fields of the North American Regional Reanalysis (NARR). They include studies of the nature and role of the LLJ (*e.g.*, Weaver and Nigam, 2008), land-atmosphere interactions (*e.g.*, Luo *et al*., 2007), and efforts to validate precipitation processes in global climate models (*e.g.*, Lee *et al*., 2007).

The above studies highlight the leading role of reanalysis data in the diagnostic evaluation of large-scale climate variability and of the physical mechanisms that produce high impact regional climate anomalies.

While reanalysis data have played a fundamental role in diagnostic studies of the leading modes of middle- and high- latitude variability and of regional climate anomalies, there are deficiencies that are particularly apparent in the stratosphere – a region of the atmosphere particularly poorly resolved in the first-generation reanalysis systems (*e.g.*, Pawson and Fiorino, 1998a; 1998b; 1999; Santer *et al*., 2003). Figure 2.10 shows an example of the substantial differences between the reanalyses that occur in the tropical stratosphere even in such a basic feature as the annual cycle of temperature.

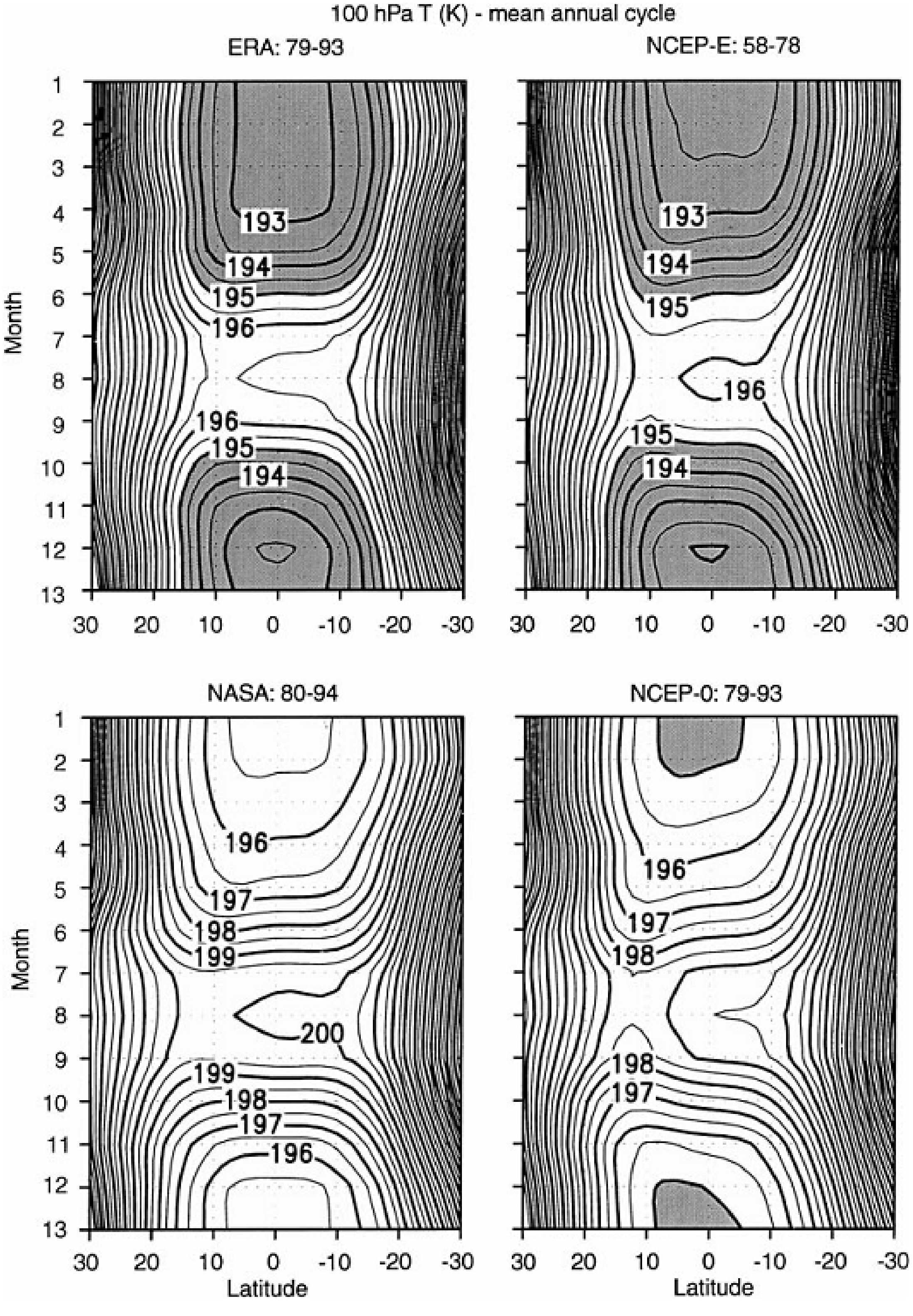

Figure 2.10 Latitudinal structure of the annual cycle in T(K) at 100 hPa for ERA (1979 to 1993, top left), NCEP-O (1958 to 1978, top right), NASA/DAO (1980 to 1994, bottom left), and NCEP-E(1979 to 1993, bottom right). The contour interval is 0.5 K. Temperatures lower than 195 K are shaded. Taken from Pawson and Fiorino (1999).

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Another key problem area is in polar regions where the reanalysis models have deficiencies in both the numerical representation and in modeling of physical processes (*e.g.*, Walsh and Chapman, 1998; Cullather *et al*., 2000, Bromwich and Wang, 2005; Bromwich *et al*., 2007). Reanalyses to date are particularly deficient in the modeled polar cloud properties and associated radiative fluxes (*e.g.*, Serreze *et al*., 1998).

Variations in tropical sea surface temperatures, particularly those associated with ENSO, are a major contributor to climate variability over North America on interannual time scales (*e.g.*, Trenberth *et al*., 1998). Recent studies that use reanalysis data have contributed to important new insights on the linkages between tropical Pacific sea surface temperature variability and the extratropical circulation (*e.g.*, Sardeshmukh *et al*., 2000; Hoerling and Kumar, 2002; DeWeaver and Nigam, 2002), the global extent of the ENSO response (*e.g.*, Mo, 2000; Trenberth and Caron, 2000), and its impact on weather (*e.g.*, Compo *et al*., 2001; Gulev *et al*., 2001; Hodges *et al*., 2003; Raible, 2007; Schubert *et al*., 2008). An important aspect of many of the studies cited above is that they include companion model simulation experiments. In such studies the reanalyses are used to both characterize the atmospheric behavior and to validate the model results. This is an important advance in climate diagnosis resulting from increased confidence in climate models, and represents an important synergy between reanalysis and the attribution studies discussed in the next chapter.

While the reanalyses have proven themselves useful in many respects for addressing the problem of tropical/extratropical connections, they do have important deficiencies in representing tropical precipitation, clouds and other aspects of the hydrological cycle (*e.g.*, Newman *et al*., 2000). The Madden-Julian Oscillation or MJO is an example of a phenomenon where coupling between the circulation and tropical heating is fundamental to its structure and evolution (*e.g.*, Lin *et al*., 2004) – a coupling that is poorly represented in climate models. Current reanalysis products are inadequate for validating models, since those aspects of the MJO that appear to be critical for the proper simulation of the MJO (*e.g.*, the vertical distribution of heating) are poorly constrained by the observations and therefore are highly dependent on the models used in the assimilation systems (*e.g.*, Tian *et al*., 2006). Nevertheless, indirect (residual) approaches to estimating the tropical forcing from reanalyses have proven themselves useful, reflecting the greater confidence placed in the estimates of certain aspects of the large-scale tropical circulation (Newman *et al*., 2000; Nigam *et al*., 2000)

While the NAO, PNA and ENSO phenomena notably influence subseasonal to interannual climate variability, there is evidence that these modes also may vary on decadal or longer time scales. Understanding that behavior, as well as other possibly intrinsically decadal-scale modes of variability such as the PDO and the AMO require datasets that are consistent over many decades. We examine next the capacity of current reanalyses to address such longer time scale variability.

2.3.2.2 Temporal characteristics

A defining characteristic of the observing system of the last 100 years or so is that it varies greatly over time. Prior to the mid 20th century, the observing system was primarily surface-based and limited to land areas and ship reports, though some upper observations (*e.g.*, wind measurements from pilot balloons) were made routinely since the early 20th century (*e.g.*, Brönnimann *et al*., 2005). The 1950s marked the beginning of an upper air radiosonde network of observations, though these were primarily confined to land areas and especially Northern Hemisphere middle latitudes. The advent of satellite observations in the 1970s marked the beginning of a truly global observing system, with numerous changes subsequently to the observing system as new satellites were launched with updated and more capable sensors, and older systems were discontinued (Figure 2.2). This, together with sensor changes and the aging and degrading of existing sensors, makes the problem of combining all available observations into a temporally consistent long-term global climate record a tremendous challenge. Figure 2.11 provides an overview of the number of observations that were available to the NCEP/NCAR reanalysis (Kistler *et al*., 2001). These changes, especially the advent of satellite observations, have impacted the reanalysis fields, often making it difficult to separate true climate variations from artificial changes associated with the evolving observing system.

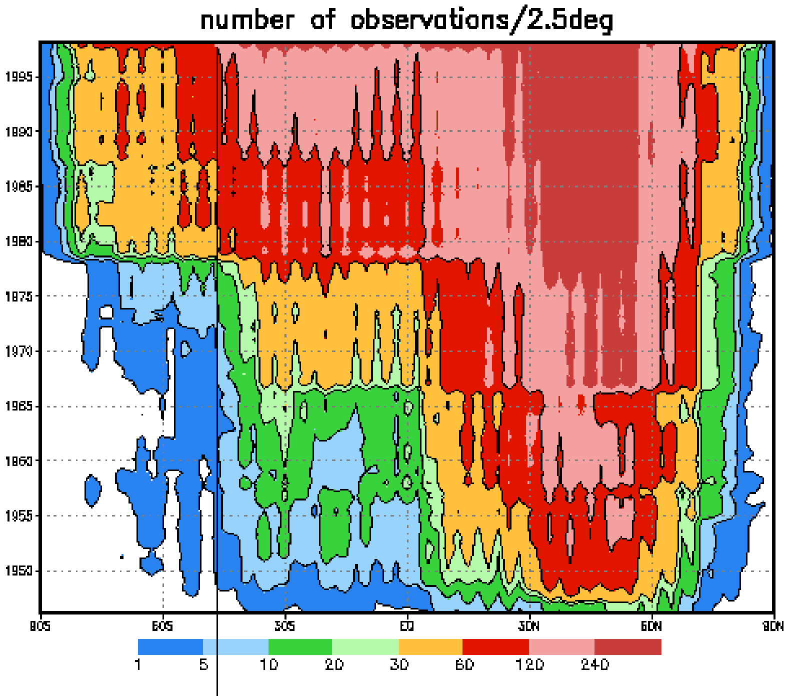

Figure 2.11 Zonal mean number of all types of observations available to the NCEP/NCAR reanalysis per 2.5° lat-long box per month from 1946 to 1998. A 12-month running mean has been applied. From Kistler *et al.* (2001)

The changes in the observing system have especially impacted our ability to study variability on interannual and longer time scales – the time scales at which changes to the observing system also tend to occur (*e.g.*, Basist and Chelliah, 1997; Chelliah and Ropelewski, 2000; Kistler *et al.*, 2001; Trenberth *et al.*, 2001; Kinter *et al.*, 2004). The impact can be quite complicated, involving interactions and feedbacks with the assimilation schemes. For example, Trenberth *et al.* (2001) show how discontinuities in tropical temperature and moisture fields can be traced to the bias correction of satellite radiances in the ECMWF (ERA-15) reanalyses. Changes in the conventional radiosonde observations can also have impacts. For example the QBO, while clearly evident throughout the record of the NCEP/NCAR reanalysis, shows substantial secular changes in amplitude that are apparently the result of changes in the availability of tropical wind observations (Kistler *et al*., 2001). The major change in the observing system associated with the advent of satellite data in the 1970s represents a particularly difficult and important problem since it coincides with the time of a major climate shift associated with the PDO (*e.g.*, Pawson and Fiorino, 1999; Trenberth and Caron, 2000; Chelliah and Bell, 2004).

Despite these problems, reanalysis data can be very valuable in understanding long-term atmospheric variability, particularly if used in conjunction with other independent data. For example, Barlow *et al*. (2001) used NCEP/NCAR reanalyses of winds and stream function for the period 1958 to 1993, in conjunction with independent sea surface temperature, stream-flow, precipitation and other data to identify three leading modes of sea surface temperature variability affecting long-term drought over the United States.

A broad-brush assessment of the quality of the reanalyses is that the quality tends to be best at weather time scales and degrades as we go to both shorter and longer time scales. The changes in quality reflect both the changes in the observing system and the ability of the model to simulate the variability at the different time scales. At time scales of less than a day, deficiencies in model representation of the diurnal cycle, shocks associated with the insertion of observations, and an observing system that does not fully resolve the diurnal cycle combine to degrade analysis quality (*e.g.*, Higgins *et al*., 1996; Betts *et al*., 1998a). This problem contributes to errors in our estimates of seasonal and longer time averages as well. Unsurprisingly, the quality is best for weather time scales (*e.g.*, Beljaars *et al*., 2006) of one day to a week, given that the analysis systems and models used for atmospheric reanalyses so far were developed for numerical weather prediction. At interannual and longer time scales, the impact of the major atmospheric observing system changes, combined with the increasingly important connections with other components of the climate system, contribute to degrading reanalysis quality.

We emphasize here the important connections the atmosphere has to the land and ocean on seasonal and longer time scales. The assimilation systems for both these components are considerably less mature than for the atmosphere (discussed further in section 2.5). In fact, in the current generation of atmospheric reanalyses, the connection with the ocean is made by specifying sea surface temperatures from reconstructions of historical observations, and the land is represented in a very simplified form. We note that the simplified representation of the land can also contribute to deficiencies in representing the diurnal cycle, which is highly coupled to the land surface (*e.g.*, Betts *et al*., 1998b).

Model errors can have especially large impacts on quantities linked to the hydrological cycle such as atmospheric water vapor (*e.g.*, Trenberth *et al*., 2005) and major tropical circulations of relevance to understanding climate variations and change, such as the Hadley Cell (Mitas and Clement, 2006). Any bias in the model can, in fact, exacerbate spurious climate signals associated with a changing observing system. An example is a model that is consistently too dry in the lower atmosphere. Such a model may give a realistic tropical precipitation field when there are few moisture observations available to constrain the model, but that same model can produce very unrealistic rainfall when it is confronted with large amounts of water vapor information such as that coming from satellite instruments beginning in the late 1980s (Figure 2.5).

The impacts of the changing observing systems on current reanalysis products reflect the fact that little has been done to try to account for these changes. The philosophy to date has been to use all available observations in order to maximize the accuracy of the reanalysis products at any given time, while little consideration has been given to developing approaches that could ameliorate the temporal inhomogeneities over long time periods in the reanalysis products. This defect has been recognized, and efforts are now under way to carry out reanalyses with reduced observing systems that are fixed over time (*e.g.*, Compo *et al*., 2006), as well as other observing system sensitivity experiments that could help to understand if not ameliorate the impacts (*e.g.*, Bengtsson *et al*., 2004b,c; Dee, 2005; Kanamitsu and Hwang, 2006). Other efforts that can help include: model bias correction techniques (*e.g.*, Dee and da Silva, 1998; Chepurin *et al*., 2005; Danforth *et al*., 2007), improvements to our models (Grassl, 2000; Randall, 2000), and improvements to historical observations including data mining, improved quality control and further cross calibration and bias correction of observations (Schubert *et al*., 2006).

We next consider to what extent they are internally consistent. For example do they provide realistic surface fluxes that are consistent with the other components of the climate system (in particular the land and ocean), and moisture and energy budgets that are balanced?

2.3.2.3 Internal consistency and scope

One advantage of reanalysis products mentioned earlier involves the role of the model in providing internal consistency. By this we mean that the model enforces certain dynamical balances on the reanalysis fields that are known to exist in the atmosphere. An example is the tendency for the atmosphere to be in geostrophic balance (an approximate balance of the Coriolis and pressure gradient forces) in middle latitudes. One important implication is that the different state variables (the quantities that define the state of the atmosphere – *e.g.*, the winds, temperature and pressure) cannot take on arbitrary values but instead depend strongly on each other. That such constraints are satisfied in the reanalysis products is important for many studies that attempt to understand the physical processes or forcing mechanisms by which the atmosphere evolves (*e.g.*, the various patterns of variability mentioned above).

This, in fact, is at the heart of one fundamental advantage of model-based reanalysis products over univariate analyses of, say, temperature or water vapor observations. Reanalysis products provide us at any one time with a full multivariate, globally complete picture of the atmosphere together with the various forcing functions that determine how the atmosphere evolves in time. As such, in principle we are able to diagnose all aspects of how the climate system has evolved over the time period covered by the reanalyses. There is of course a key caveat: the results depend on the quality of the model as well as characteristics of model and observational errors used in the reanalysis. As mentioned earlier, the models used in the current generation of reanalyses were largely developed for middle-latitude numerical weather prediction, and have known deficiencies, especially in various components of the hydrological cycle (clouds, precipitation, evaporation) that are critical for understanding such important phenomena as the monsoons, droughts, and various tropical phenomena.

Given that models are imperfect, can model-based reanalysis products be used to validate model simulations (see also discussion in the previous section)? For example, by forcing models with the historical record of observed sea-surface temperatures, can we reproduce some of the major precipitation anomalies of the last hundred years or so (*e.g.*, Hoerling and Kumar, 2003; Schubert *et al*., 2004; Seager *et al*., 2005; see next chapter on attribution)? As we diagnose these simulations for clues about how the climate system operates, there is an increasing need to validate the physical processes that produce the regional climate anomalies (*e.g.*, drought in the Great Plains of the United States). There is a legitimate question over whether the reanalyses used in the validations are themselves compromised by model errors. However, evidence is growing that, at least in regions with relatively good data coverage, the reanalyses can be used to identify fundamental errors in the model forcing of hydrological climate anomalies (*e.g.*, Ruiz-Barradas and Nigam, 2005).

On global scales, the deficiencies in the assimilation models manifest themselves as biases in, for example, monthly mean budgets of heat and moisture, and therefore introduce uncertainties in the physical processes that contribute to such budgets (*e.g.*, Trenberth and Guillemot, 1998; Trenberth *et al*., 2001; Kistler *et al*., 2001). While there has been some success in looking at variability of the energy budgets associated with some of the major climate variations such as ENSO (*e.g.* Trenberth *et al*., 2002a), inconsistencies in certain budgets (especially the atmospheric energy transports) limit their usefulness for estimating net surface fluxes (Trenberth and Caron, 2001) - quantities that are a crucial for linking the atmosphere and the ocean, as well as the atmosphere and land surface. Deficiencies in the model-estimated clouds (and especially the short wave radiation) appear to be a primary source of the problems in the model fluxes both at the surface and the top of the atmosphere (*e.g.*, Shinoda *et al*., 1999). Figure 2.12 shows an example of estimates of the implied ocean heat transport provided by two different reanalyses and how they compare with the values obtained from a number of different coupled atmosphere-ocean model simulations.

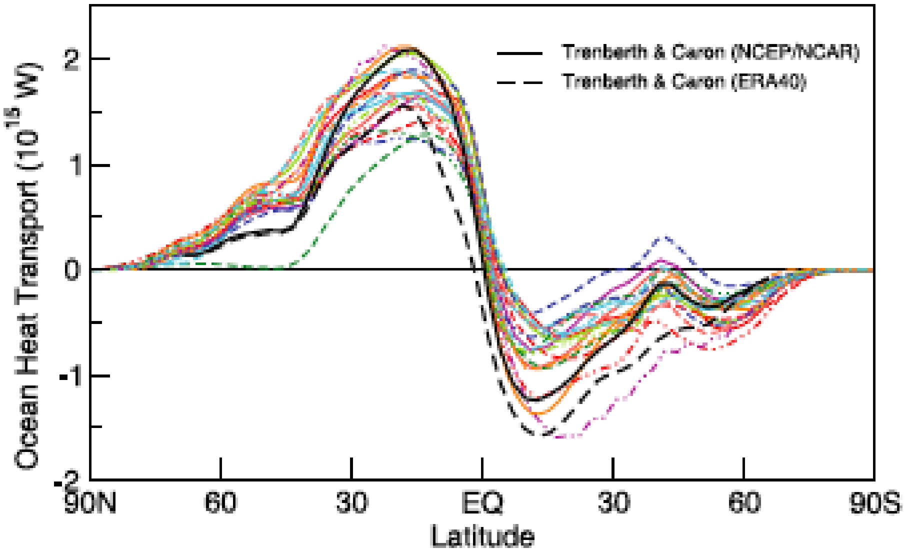

Figure 2.12 Annual mean, zonally averaged oceanic heat transport implied by net heat flux imbalances at the sea surface, under an assumption of negligible changes in oceanic heat content. The observationally based estimate, taken from Trenberth and Caron (2001) for the period February 1985 to April 1989, derives from reanalysis products from the National Centers for Environmental Prediction (NCEP)/NCAR (Kalnay *et al*., 1996) and European Centre for Medium Range Weather Forecasts 40-year reanalysis (ERA40;

Uppala *et al*., 2005). The model climatologies are derived from the years 1980 to 1999 in the 20th century simulations in the MMD at PCMDI. The legend identifying individual models appears in Figure 8.4 of the AR4 IPCC report (taken from chapter 8 of the IPCC AR4 report).

The internal consistency problem is compounded by the fact that current atmospheric reanalysis models do not satisfactorily represent interactions with other important components of the climate system (ocean, land surface, cryosphere). One result of this limitation is that the various surface fluxes (*e.g.*, precipitation, evaporation, radiation) at the interfaces between the land and atmosphere, and the ocean and atmosphere, are generally inconsistent with each other and therefore limit our ability to fully understand the forcings and interactions of the climate system (*e.g.*, Trenberth *et al*., 2001). While there are now important stand-alone land (*e.g.*, Reichle and Koster, 2005) and ocean (*e.g.*, Carton *et al*., 2000) reanalysis efforts in development or underway (see section 2.5), the long-term goal is a fully coupled climate reanalysis system (Tribbia *et al*., 2003).

2.4 TO WHAT EXTENT IS THERE AGREEMENT OR DISAGREEMENT BETWEEN CLIMATE TRENDS IN SURFACE TEMPERATURE AND PRECIPITATION DERIVED FROM REANALYSES AND THOSE DERIVED FROM INDEPENDENT DATA?

The climate of a region is defined by statistical properties of the climate system (*e.g.*, means, variances and other statistical measures) evaluated over an extended period of time, typically on the order of decades or longer. If these underlying statistical values do not change with time, the climate would be referred to as "stationary". For example, in a stationary climate a region's average monthly rainfall, say, during the 20th century would be the same as that in the 19th, 18th, or any other century (within statistical sampling errors). Climate, however, is fundamentally non-stationary; the underlying averages (and other statistical measures) do change over time. The climate system varies through ice ages and warmer periods with a timescale of about 100,000 years (Hays *et al*., 1976). The "Little Ice Age" in the 15th to 19th centuries (Bradley *et al*., 2003) is an example of a natural climate variation (an example of non-stationarity) with a much shorter timescale of a few centuries. Humans may be affecting climate even more quickly through their impact on atmospheric greenhouse gases (Hansen *et al*., 1981).

The search for trends in climatic data is, in essence, an attempt to quantify the non-stationarity of climate, as reflected in changes in long-term climate mean values. There are various methods for accomplishing this task (see CCSP SAP 1.1, Appendix 2.A for a more detailed discussion). Perhaps the most common approach to calculating a trend from a multi-decadal dataset is to plot the data value of interest (*e.g.*, rainfall) against the year of measurement. A line is fit through the points using standard regression techniques, and the resulting slope of the line is a measure of the climatic trend. A positive slope, for example, suggests that the "underlying climatic average" of rainfall is increasing with time over the period of interest. Such a trend calculation is limited by the overall noisiness of the data and by the length of the record considered.

Reanalysis datasets now span several decades, as do various ground-based and space-based measurement datasets. Trends can be computed from both. A natural question is: how well do the trends computed from the reanalysis data agree with those computed from independent datasets? This is one method for assessing the adequacy of reanalysis data for evaluating climate trends.

This question has been addressed in many independent studies. Here we focus on trends in two particular variables, surface temperature (or, more specifically, two meter height temperature, referred to here as T2M) and precipitation. Section 2.4.1 below describes the basic finding: reanalysis-based trends, though reasonable for T2M during certain periods, often do not agree with those derived from ground-based measurements. The reasons for the differences are many, as outlined in Section 2.4.2.

2.4.1. Trend Comparisons: Reanalyses Versus Independent Measurements

Simmons *et al*. (2004) provide the most comprehensive evaluation to date of reanalysis-based trends in surface temperature, T2M. Figure 2.13, reproduced from that work, shows their main result.

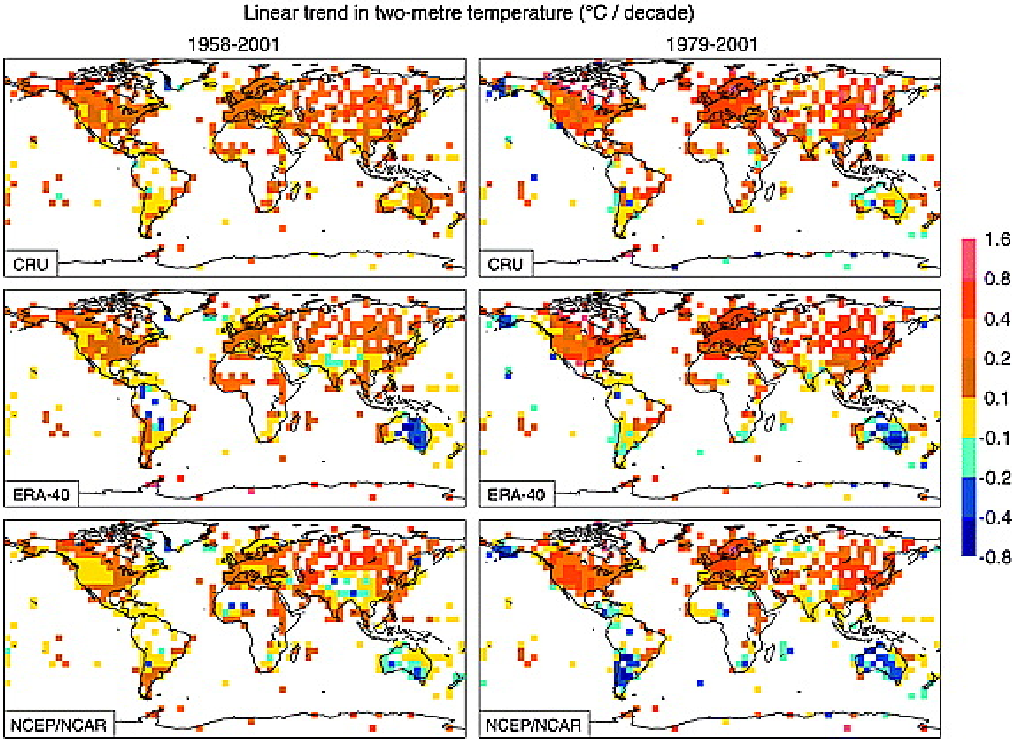

Figure 2.13. Trends in near-surface (2 meter) temperature inherent in an observational dataset (top), the ERA-40 reanalysis (middle), and the NCEP/NCAR reanalysis (bottom). Reproduced from Simmons *et al*., 2004).

Linear regression was used, as described above, to determine trends from a purely observational T2M dataset (the CRUTEM2v dataset of Jones and Moberg, 2003), from the ERA-40 reanalysis, and from the NCEP/NCAR reanalysis. Two different time periods (1958 to 2001 on the left and 1979 to 2001 on the right) were considered. All three datasets show generally positive trends. The reanalyses-based trends, however, are generally smaller, particularly for the longer time period: the average trend for 1958 to 2001 in the Northern Hemisphere, in ^{o}C per decade, is 0.19 for the observations, 0.13 for ERA-40, and 0.14 for NCEP/NCAR. For the shorter and more recent period, the Northern Hemisphere averages are 0.30 for the observations, 0.27 for ERA-40, and 0.19 for NCEP/NCAR. Simmons *et al*. (2004) consider the latter result for ERA-40 to be particularly encouraging; they emphasize "the agreement to within ~10% in the rate of warming of the terrestrial Northern Hemisphere since the late 1970s." Stendel *et al*. (2000) note that for the ERA-15 reanalysis, which covers 1979 to 1993 using an earlier version of the modeling system, the trend in T2M over North America and Eurasia is too small by 0.14° C per decade, relative to observations. Thus, in terms of temperature trends, the later ERA-40 reanalysis appears to improve significantly over the earlier ERA-15 reanalysis. Note from Figure 2.13 that the performance of ERA-40 and NCEP/NCAR varies spatially, with some very clear areas of large discrepancies that most likely represent reanalysis errors. Both reanalyses, for example, underestimate trends in India and grossly underestimate them in Australia. The NCEP/NCAR reanalysis does a particularly poor job in southern South America, a problem also noted by Rusticucci and Kousky (2002).

A similarly comprehensive evaluation of precipitation trends from reanalyses has not been published. Takahashi *et al*. (2006), however, do summarize the trends in total tropical (30°S – 30°N) precipitation over the relatively short period of 1979 to 2001 (Figure 2.14).

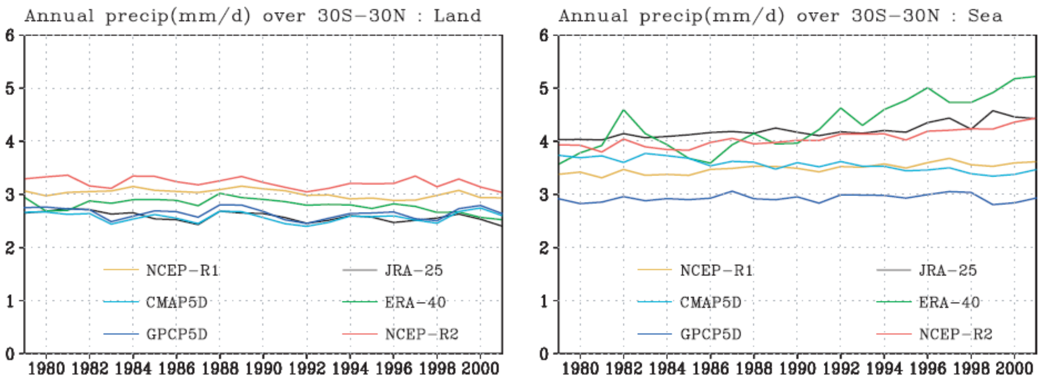

Figure 2.14. Annual tropical precipitation over land (left) and ocean (right) versus year from four reanalyses (NCEP-R1, NCEP-R2, JRA-25, and ERA-40) and from two observational datasets (CMAP5D and GCPC5D). Reprinted from Takahashi *et al*. (2006).

The biggest discrepancy between the observations and reanalyses is the large positive trend over ocean for ERA-40 and the smaller but still positive trends for the other reanalyses, trends that are not found in the observations. Similarly, Chen and Bosilovich (2007) show that the reanalyses produce a positive precipitation trend in the 1990s when global precipitation totals are considered, whereas observational datasets do not. By starting in 1979, the tropical analysis of Takahashi *et al*. (2006) misses a problem unearthed by Kinter *et al*. (2004), who demonstrate a spurious precipitation trend produced by the NCEP/NCAR reanalysis in equatorial Brazil. As shown in Figure 2.15, NCEP/NCAR produces a strong – and apparently unrealistic – increase in rainfall starting in about 1973, and thus an unrealistic wetting trend.

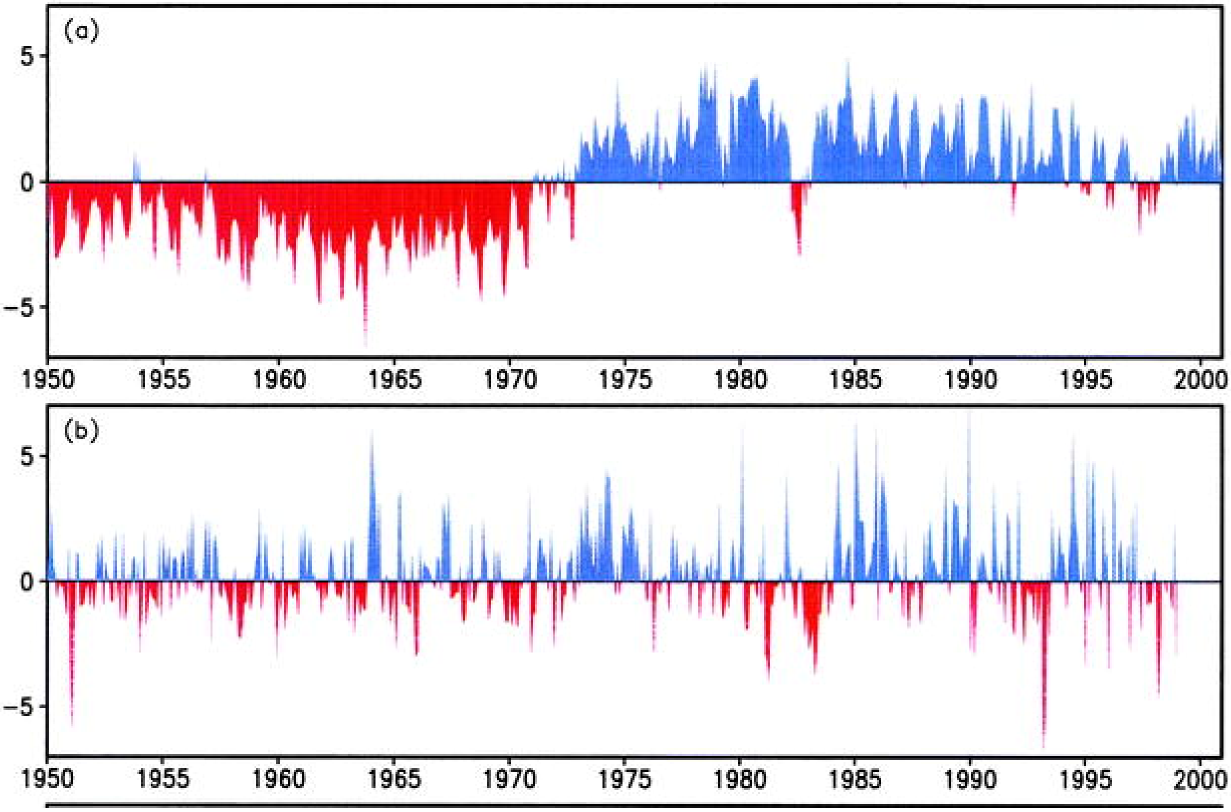

Figure 2.15. Time series of precipitation averaged over 10°S-equator, 55°-45°W, from (a) the NCAR/NCEP reanalysis, and (b) from an observational precipitation dataset. Reprinted from Kinter *et al.* (2004).

Similarly, Pohlmann and Greatbatch (2006) found that the NCEP/NCAR reanalysis greatly overestimates precipitation in northern Africa before the late 1960's but not subsequently, producing an unrealistic drying trend. Pavelsky and Smith (2006), in an analysis of river discharge to the Arctic Ocean, compared precipitation trends in the ERA-40 and NCEP/NCAR reanalyses with those from ground-based observations and found the reanalyses trends to be much too large, particularly for ERA-40. Figure 2.16 qualitatively summarizes these results.

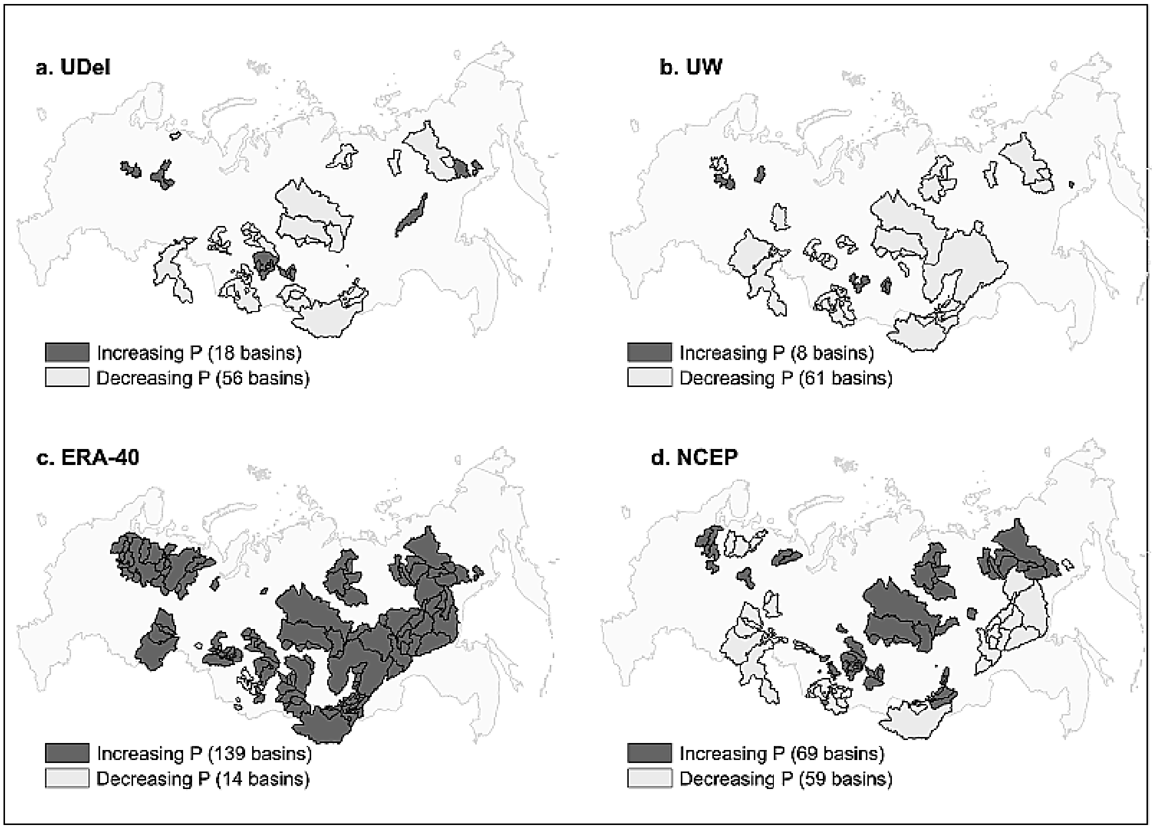

Figure 2.16. Identification of northern Asia river basins for which the computed precipitation trend is positive (a wetting trend) or negative (a drying trend), for four datasets: (top left) a dataset based on ground-based measurements of rainfall; (top right) a modified (improved) version of the first dataset; (bottom left) the ERA-40 reanalysis; and (bottom right) the NCEP/NCAR reanalysis. From Pavelsky and Smith (2006).

Identified for each dataset are the river basins with an increasing precipitation trend and those with a decreasing precipitation trend. For ERA-40, the vast majority of basins show an unrealistic (relative to ground observations) wetting trend.

2.4.2. Factors Complicating the Calculation of Trends

In summary, the previous studies indicate that observed temperature trends appear to be captured to first order by the reanalyses, particularly in the latter part of the record, though some problem areas (*e.g.*, Australia) show up clearly. Reanalysis-based precipitation trends appear to be much less consistent with those calculated from observational datasets. As described below, many studies have identified sources for errors with the reanalyses that can at least partly explain these deficiencies. It must be kept in mind, however, that trends produced from the observational datasets are themselves subject to errors for a number of reasons (see CCSP SAP 1.1, and also discussed below), so that the true deficiencies of the reanalyses-based trends cannot be wholly known.

First, and perhaps most important, a spurious trend in the reanalysis data may result from a change in the observations being assimilated. In particular, the late 1970s saw the advent of satellite data, an unprecedented increase of global-scale observations of highly variable quality. Consider now the example of a model that tends to "run cold" (has a negative temperature bias) when not constrained by data. Suppose this model is used to perform a reanalysis of the last 50 years but by necessity only ingests satellite data from the late 1970s onward. The first half of the reanalysis will be biased cold relative to the second half, leading to an artificial positive temperature trend (Figure 2.17).

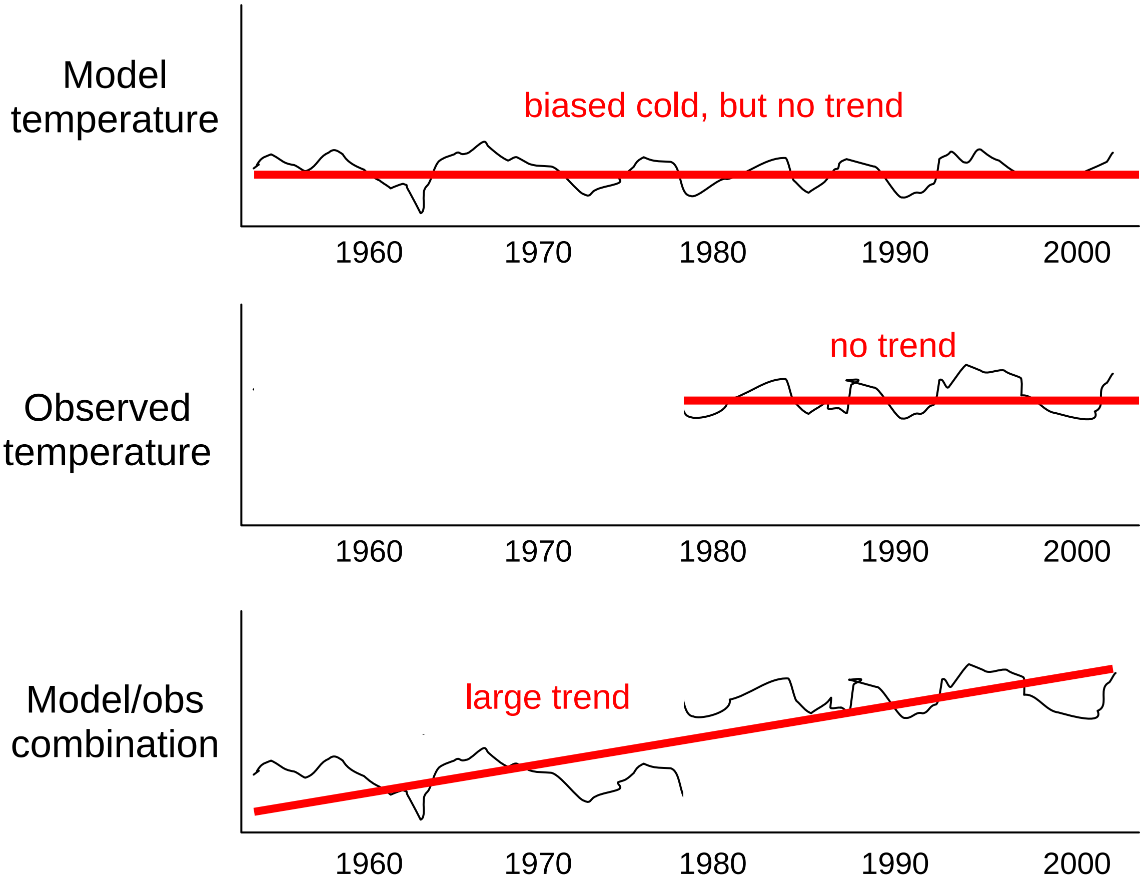

Figure 2.17 Idealized example showing how the correction of biased model data with observational data during only one part of a reanalysis period (in this case, from 1979 onward) can lead to a spurious temporal trend in the reanalysis product.

Bengtsson *et al*. (2004a) use this reasoning to explain an apparently spurious trend in lower troposphere temperature (not surface temperature) produced by the ERA40 reanalysis. Kalnay *et al*. (2006), when computing trends in surface air temperature from the NCEP/NCAR reanalysis, separate the 40-year reanalysis period into a pre-satellite and post-satellite period to avoid such issues. Note, however, that reanalyses are affected by other (non-satellite) measurement system changes as well. Betts *et al*. (2005) note in reference to the surface temperature bias over Brazil that "the Brazilian surface synoptic data are not included [in the ERA-40 reanalysis] before 1967, and with its introduction, there is a marked shift in ERA-40 from a warm to a cool bias in 2-m temperature."

Also, reanalyses that rely solely on the ingestion of atmospheric data may miss real trends in surface temperature that are associated with urbanization, cropland conversion, changing irrigation practices, and other land use changes (Pielke *et al*., 1999; Kalnay *et al*., 2006). The ERA-40 reanalysis, which does assimilate some station-based surface air temperature measurements, is less affected by this issue than the NCEP/NCAR reanalysis, which does not. This difference in station data assimilation may explain some (though not all) of ERA-40's better performance in Figure 2.13 (Simmons *et al*., 2004).

As mentioned above, calculating trends from observational datasets (the "truth" used for the evaluation of reanalysis-based trends) also involves errors, and introduces additional uncertainties when compared with reanalysis products for which values are provided on regular grids. For example, an important and challenging issue is estimating the appropriate grid-cell averaged temperature and precipitation values from point observations so that they can be directly compared with reanalysis products. Errors in representation may play a particularly important role. For example, the rain falling at one observation point may not be (and in fact, generally is not) representative of the rain falling over the corresponding model grid cell (which represents an area-average value). Rainfall measurements themselves are often sparse and distributed non-randomly, *e.g.*, in the mountainous western United States, much of the precipitation falls as snow at high mountain elevations, while most direct measurements are taken in cities and airports located at much lower elevations. Simmons *et al*. (2004) note that the gridded observational values along coastlines reflect mostly land-based measurements, whereas reanalysis values for coastal grid cells reflect a mixture of ocean and land conditions. Producing a gridded data value from multiple stations within the cell can lead to significant problems for trend estimation, since the contributing stations may have different record lengths and other spatial and temporal inhomogeneities (Hamlet and Lettenmaier, 2005). Jones *et al*. (1999) note that urbanization – urban development over time in the area of a sensor – can produce a positive temperature trend at the sensor that is quite real, but is also unrepresentative of the large grid cell that contains it.

Multi-decadal observational datasets are also strongly subject to changes in measurement systems. Takahashi *et al*. (2006) suggest that the use, starting in 1987, of a new satellite data product in an observational precipitation dataset led to a change that year in the character of the data. Kalnay *et al*. (2006) point to an artificial trend in observational temperature data induced by changes in measurement time-of-day, measurement location, and thermometer type. Jones *et al*. (1999) discuss the need, prior to computing trends, of adjusting or omitting station data as necessary to ensure a minimal impact of such changes.

Figure 2.18 gives a sense for the uncertainty inherent in trend computations from observational datasets.

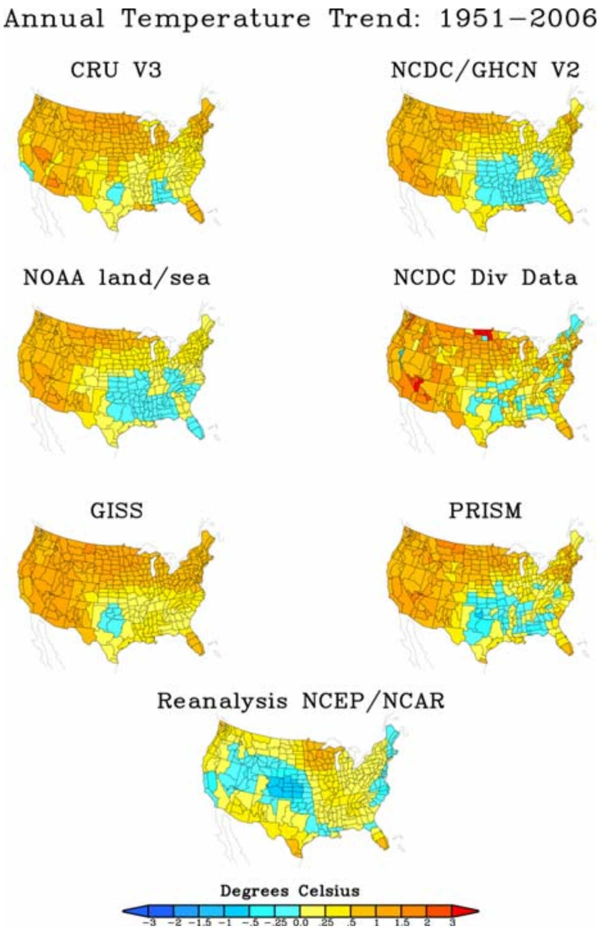

Figure 2.18. Annual temperature trends across the continental United States, as determined with six observational datasets and the NCEP/NCAR reanalysis (M. Hoerling, personal communication).

The top six maps show the spatial distributions (across the continental United States) of annual temperature trend as computed from six different datasets spanning 1951 to 2006, and the bottom map shows the trend computed from the NCEP/NCAR reanalysis. Of the seven maps, the reanalysis-derived map is clearly the outlier; the six observations-based maps all show a warming trend everywhere but in the South, whereas the reanalysis shows a general warming in the South and cooling toward the west. Even so, the six observations-based maps do not fully agree. The spatial extent of the cooling in the South is smaller in the GISS and CRU datasets than it is in the NCDC/GCHN dataset. The

NCDC climate division data show relatively high trend values in the west. Therefore it is important to recognize that we have no perfect "truth" against which to evaluate the reanalysis-based trends.

Other sources of uncertainty for both observations-based trends and reanalysis-based trends also merit mention. The mathematical algorithm used to compute the trends is important. Jones (1994a) uses the linear regression approach described above and the "robust trend method" of Hoaglin *et al*. (1983) and thereby computes two sets of trend values (similar, but not identical) from the same dataset. Also, part of the trend estimation problem is determining whether a computed trend is real, that is, the degree to which the trend is unlikely to be the result of statistical sampling variations. Groisman *et al*. (2004) describe a procedure they used to determine the statistical significance of computed trends. Even if all surface temperature data were perfect and the trend estimation technique was not an issue, the time period chosen for computing a trend can result in sampling variations, depending (for example) on the relationship to transient events such as ENSO or volcanoes (Jones, 1994b).

2.4.3. Outlook

While the above limitations hamper the accurate estimation of trends from either reanalyses or observational datasets, it is our assessment that it is likely that most of the trend differences shown in Figures 2.13 to 2.16 are related to limitations of the model-based reanalyses. Data sets that are derived directly from surface and/or satellite observations (such as those for surface air temperature, precipitation, atmospheric water vapor) will continue, at least for the near-term, to be the main tool for quantifying decadal and long-term climate changes. The observations-based trends are likely to be more trustworthy, partly because the relevant limitations in the observational data are better known and can, to a degree, be accounted for prior to trend estimation. This is less the case for existing reanalyses, which were not originally designed to be optimized for trend detection. Bengtsson *et al*. (2004a), examining various reanalysis products (though not surface temperature or precipitation), find that "there is a great deal of uncertainty in the calculation of trends from present reanalyses...". Note that reanalysis-based precipitation (for ERA-40 and NCAR/NCEP) and surface air temperature (for NCAR/NCEP) are derived solely from the models (*i.e.*, precipitation and surface temperature observations are not assimilated). Therefore, these fields are subject to inadequacies in model parameterization. The North American Regional Reanalysis is an important example of a reanalysis project that did employ the assimilation of observed precipitation data (Mesinger *et al*., 2006), producing, as a result, more realistic precipitation products.

It should be noted that reanalyses do have at least one advantage in analyzing trends. The complexity of describing and understanding trends is multi-faceted, and involves more than simply changes in mean quantities over time. Precipitation trends, for example, can be examined in the context of the "shape parameters" of precipitation probability distributions rather than total precipitation amount (Zolina *et al*., 2004). Observed precipitation trends in the United States reflect more than just an increase in the mean itself, being largely related to increases in extreme and heavy rainfall events (Karl and

Knight, 1998). Over tropical land, on the other hand, heavier rainfall events seem to be decreasing over the last 20 years, a trend that does, in fact, appear to be captured by reanalyses (Takahashi *et al*., 2006). Warming trends often reflect nighttime warming rather than warming throughout the full 24-hour day (Karl *et al*., 1991). Precipitation and temperature statistics are fundamentally tied together (Trenberth and Shea, 2005), so that precipitation and temperature trends should not be studied in isolation.

Given these (and other) examples of trend complexity, one advantage of a reanalysis dataset becomes clear: a proper analysis of the mechanisms of climate trends requires substantial data, and only a reanalysis provides self-consistent datasets that are complete in space and time over several decades. Clearly, given Figures 2.13 to 2.16, future reanalyses need to be improved to support robust trend estimation, particularly for precipitation. Climate researchers, however, may still find that for many purposes the comprehensive fields generated by reanalyses, together with their continuity (*i.e.*, none of the gaps in time that are a common feature in observational data) and spatial coverage provide value for understanding the causes of trends beyond what can be gained from observational data sets alone. For example, by providing estimates of trends in middle latitude circulation patterns and other weather elements (features that tend to have a robust signal in reanalyses – see section 2.4), reanalyses can provide insights into the nature of observed surface temperature and/or precipitation trends.

2.5 WHAT STEPS WOULD BE MOST USEFUL IN REDUCING SPURIOUS TRENDS AND OTHER MAJOR UNCERTAINTIES IN DESCRIBING THE PAST BEHAVIOR OF THE CLIMATE SYSTEM THROUGH REANALYSIS METHODS? SPECIFICALLY, WHAT CONTRIBUTIONS COULD BE MADE THROUGH IMPROVEMENTS IN DATA RECOVERY OR QUALITY CONTROL, MODELING, OR DATA ASSIMILATION TECHNIQUES?

As discussed previously, there are several reasons why our current approaches to assimilating observations for climate reanalysis can lead to spurious trends and patterns of climate variability. The instruments we use to observe the climate may contain systematic errors, and changes in the types of instruments over time may introduce false trends into the observations. Even if the instruments themselves are accurate, the spatial and temporal sampling of the instruments changes over time and thus may alias shorter time scale or smaller space scale features, or introduce spurious jumps into the climate record. In addition, the numerical models used to provide a background estimate of the system state contain systematic errors that can project onto the climate analysis. In the case of the ocean, changes in the quality of the surface meteorological forcing will be an additional source of false trends. Here we address issues of systematic instrument and data sampling errors as well as model and data assimilation errors as a backdrop for recommending improvements in the way future reanalyses are performed. Specific recommendations are given in Chapter 4.

2.5.1 Instrument and Sampling Issues

Prior to the middle of the 20th Century the atmosphere and ocean observing systems consisted mainly of surface observations of variables such as sea level pressure, winds, and surface temperature, though some upper air observations were already routinely made early in the 20th century (Brönnimann *et al*., 2005). Much of the marine surface data are already contained in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) data set (Worley *et al*., 2005) but much also remains to be included. Considerable surface land data also exist, though these are currently scattered through several data archives, including those at the National Climatic Data Center (NCDC) and National Center for Atmospheric Research (NCAR). Many additional surface datasets remain to be digitized. The state of this surface land data should improve as various land data recovery efforts get under way (Compo *et al*., 2006). Any attempt to reconstruct climate in the first half of the 20th Century must rely on these surface observations almost exclusively and thus these data recovery efforts remain a high priority (Whitaker *et al*., 2004; Compo *et al*., 2006).

In 1936, the United States Weather Bureau began operational use of the balloon-deployed radiosonde instrument, thus providing routine soundings of atmospheric pressure, temperature, humidity, wind direction and speed for daily weather forecasts. By the International Geophysical Year of 1958 the radiosonde network expanded globally to include Antarctica and became recognized as a central component of the historical observation network that climate scientists could use to study climate. As a climate observation network, radiosondes suffer from two major types of problems. First, the instruments themselves contain systematic errors (Haimberger, 2007). For example, the widely used Vaisala radiosondes exhibit a dry bias that needs to be removed (Zipser and Johnson, 1998; Wang *et al*., 2002). Second, some radiosonde stations have moved to different locations, introducing inhomogeneities in the record (Gaffen, 1994).

Two additional observing systems were added in the 1970s. Aircraft observations increased in 1973, along with some early satellite-based temperature observations. In 1978 the number of observations increased dramatically in preparation for the First GARP Global Experiment, known as FGGE. The increase in observation coverage included three satellite-based vertical temperature sounder instruments (MSU/HIRS/SSU), cloud-tracked winds, and the expansion of aircraft observations and surface observations from ocean drifters. The impact of this increase in observations (particularly dramatic in the Southern Hemisphere) has been noted in the NCEP/NCAR and NCEP/DOE reanalyses (Kalnay *et al*., 1996; Kistler *et al*., 2001).

Currently the radiosonde network consists of about 900 stations. Most of these are still launched from continents in the Northern Hemisphere. Of these stations only ~600 launch radiosondes twice a day. Most of these launches produce profiles that extend only into the lowest levels of the stratosphere, at which height the balloons burst. A further troubling aspect of the radiosonde network is the recent closure of stations, particularly in poorly sampled Africa and the countries of the former Soviet Union.

As indicated above, the number of atmospheric observations increased dramatically in the 1970s with the introduction of remotely sensed temperature retrievals, along with a succession of ancillary measurements (*e.g.*, Figure 2.1). The temperature retrievals are made by observing the intensity of upwelling radiation in the microwave and infrared bands and then using physical models to relate these intensity measurements to a particular temperature profile. Interestingly, the problem of unknown systematic errors in the observations and the need for redundant observations has been highlighted in recent years by a false cooling trend detected in microwave tropospheric temperature retrievals. This false cooling trend has recently been corrected by properly accounting for the effects of orbital decay (Mears *et al*., 2003).

Like its atmospheric counterpart, the ocean observing system has also undergone a gradual expansion of *in situ* observations followed by a dramatic increase of satellite-based observations (Figures 2.19 and 2.20).

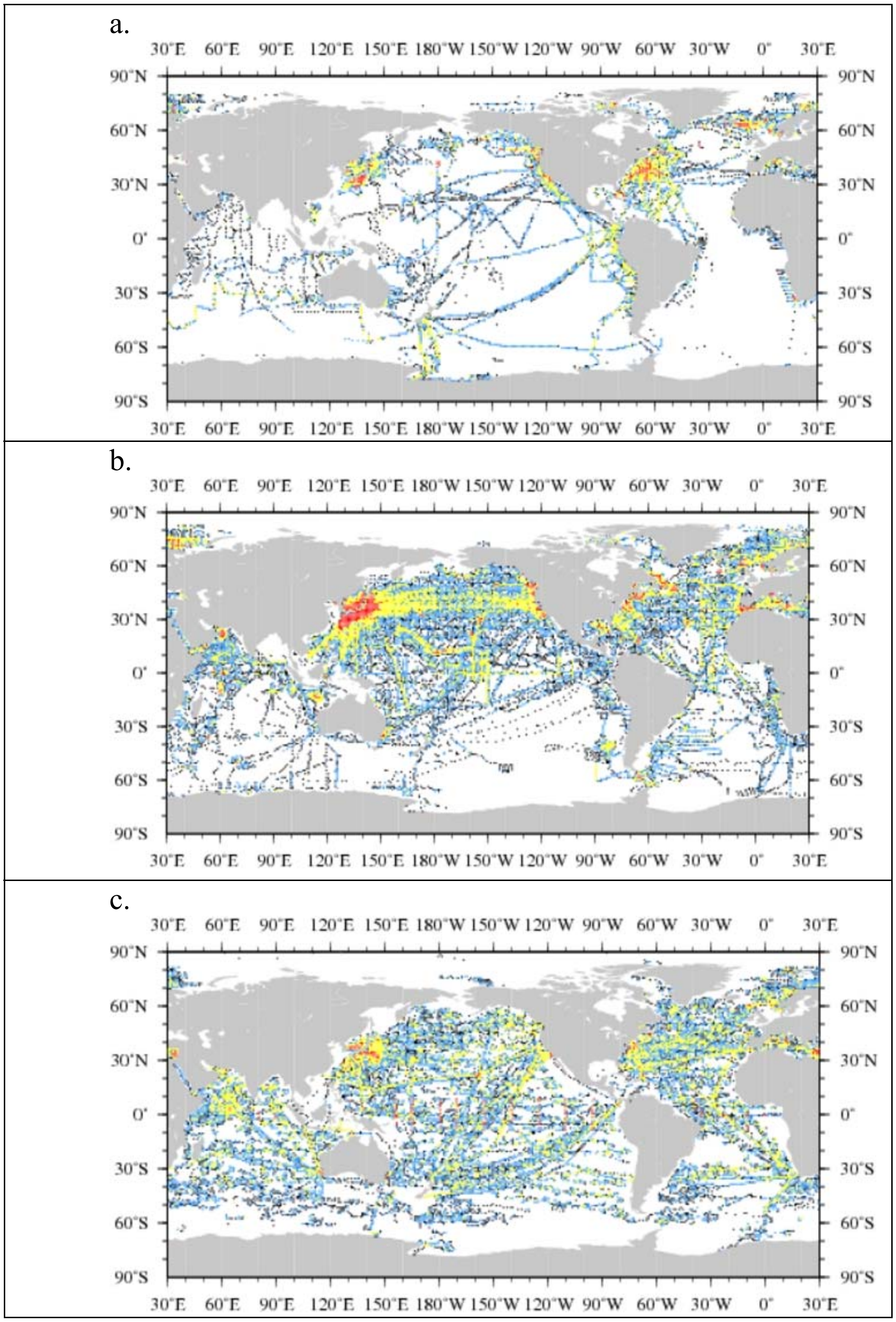

Figure 2.19 Distribution of temperature profile observations in the World Ocean Database showing 40,000 profiles extending to 150m depth for 1960 (panel a), 105,000 profiles for 1980 (panel b), and 106,000 profiles for 2004 (panel c) (http://www.nodc.noaa.gov/OC5/indprod.html).

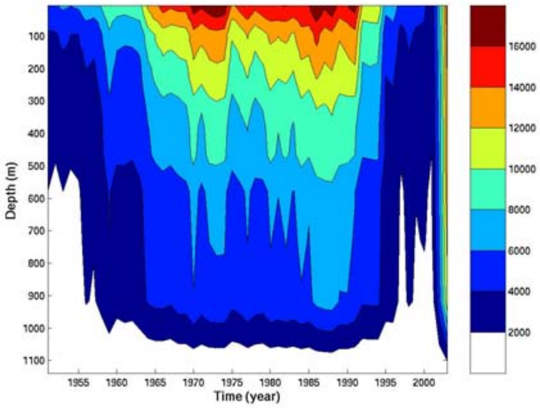

Figure 2.20 Distribution of salinity observations as a function of depth and time in the upper 1000m from the World Ocean Database 2001 (Carton and Giese, 2007). The decrease in salinity observations in 1974 resulted from the closure of the ocean weather stations, while the decrease in the mid 1990s resulted from the end of the World Ocean Circulation Experiment and the effects of the time delay in getting salinity observations into the data archives. The recent increase in salinity observations is due to the deployment of the Argo array.

Prior to 1970 the main instrument for measuring subsurface ocean temperature was the mechanical bathythermograph. This instrument was primarily deployed along trade shipping routes (Northern hemisphere) and recorded temperature only in the upper 280m, well above the oceanic thermocline at most locations. In the late 1960s the expendable bathythermograph (XBT) was introduced. In addition to being much easier to deploy, the XBT typically records temperature to a depth of 450m or 700m. Beginning in the late 1980s moored thermistor arrays have been deployed in the tropical oceans beginning with the TAO/Triton array of the tropical Pacific, but expanding into the Atlantic (PIRATA) in 1997 and most recently into the tropical Indian Ocean. These surface moorings typically measure temperature and less often salinity at fixed depths to 500m.

Two major problems have been discovered in the historical ocean temperature sampling record. The first is that much of the data were missing from the oceanographic centers.

The 1974 version of the World Ocean Atlas contained 1.5 million profiles. Thanks to great efforts by Global Oceanographic Data Archaeology and Rescue (GODAR) the latest release of the World Ocean Database (WOD2005) contains nearly 8 million profiles (Boyer *et al*., 2006). Such data archaeology and rescue work needs to be continued. A second problem arises from the fact that like its atmospheric counterpart the radiosonde, the XBT instrument was not designed for climate monitoring. XBT profiles are now known to underestimate the depth of the measurement by 1 to 2.5% of the actual depth (Hanawa *et al*., 1995). Unfortunately, the compensating drop-rate correction is different for different varieties of XBTs while less than half of the XBT observations identify the variety used. Some of the XBT observations collected since the late 1990s have already had a drop-rate correction applied without accompanying documentation, while there is evidence that the drop-rate error has changed over time, being more severe in the 1970s (AchutaRao *et al*., 2007).

For the last half of the 20th Century the main instrument for collecting deep profiles of ocean temperature as well as profiles of salinity was one or another version of the Salinity Temperature Depth or Conductivity Temperature Depth (we will refer to as the CTD) sensor. The CTD profiles are quite accurate, but are fewer in number than XBT profiles by a factor of five. As a result, diagnoses of historical changes in deep circulation must remain largely in the realm of speculation.

Since 2003 a new international observing program called Argo (Roemmich and Owens, 2000) has revolutionized ocean observation. Argo consists of a set of several thousand autonomous drifting platforms that spend most of their time at mid levels of the ocean, currently about 1000 m depth. At regular intervals, generally ten days, the Argo drifters sink and then rise to the surface, recording a profile of temperature and salinity, which is then transmitted via satellite to data archival centers. The introduction of Argo has greatly increased ocean coverage in the Southern Hemisphere and at mid-depths everywhere, and also greatly expanded the number of salinity observations. Argo is also gradually being expanded to measure variables such as Oxygen which are important for understanding the movement of greenhouse gases.

Further dramatic expansions of the ocean observing system have resulted from application of satellite remote sensing. This process began in the 1980s with the introduction of infrared and microwave sensing of sea surface temperature, followed in the early 1990s by the introduction of continuous radar observations of sea level, and then in the late 1990s with regular surface wind observations from scatterometers.

The availability of ocean data sets as well as general circulation models of the ocean has led to considerable interest in the development of ocean reanalyses (Table 2.3). The techniques being employed are rather analogous to those being employed for the atmosphere. One such example is the Simple Ocean Data Assimilation (SODA) ocean reanalysis of (Carton *et al*., 2000). Like its atmospheric counterpart, this reanalysis shows distinctly different climate variability when the massive satellite data is included.

We next turn to issues regarding the collection and interpretation of reanalysis-relevant land surface data. First, global scale *in situ* measurements of land states (soil moisture, snow, ground temperature) are essentially non-existent. Scattered measurements of soil moisture data are available in Asia (Robock *et al*., 2000), and snow measurement networks provide useful snow information in certain regions (*e.g.*, SNOTEL, <www.wcc.nrcs.usda.gov/snotel/>), but grid-scale *in situ* averages that span the globe are unavailable. Satellite data provide global coverage; however, they have their own limitations. Even the most advanced satellite-based observations can only measure soil moisture several centimeters into the soil, and not at all under dense vegetation (Entekhabi *et al*., 2004). Also, existing satellite-based estimates of surface soil moisture, as produced from different sensors and algorithms, are not consistent (Reichle *et al*., 2007), implying the need for bias correction. Time-dependent gravity measurements may provide soil moisture at deeper levels, but only at spatial scales much coarser than those needed for reanalysis (Rodell *et al*., 2007). Snow cover data from satellite are also readily available, but the estimation of total snow amount from satellite data is subject to significant uncertainty (Foster *et al*., 2005).

There are now a number of recommendations put forth by the community (*e.g.*, Schubert *et al*., 2006) to make progress on issues regarding data quality and the improvement of the world's inventories of atmospheric, ocean and land observations. These include the need for all the major data centers to prepare inventories of observations needed for reanalysis, to form collaborations that can sustain a data refresh cycle and create high quality datasets of all instruments useful for reanalyses, to develop improved record

Box 2.2 MERRA

The NASA/Global Modeling and Assimilation Office (GMAO) atmospheric global reanalysis project is called the Modern Era Retrospective-Analysis for Research and Applications (MERRA). MERRA (Bosilovich *et al*. 2006) is based on a major new version of the Goddard Earth Observing System Data Assimilation System (GEOS-5), that includes the Earth System Modeling Framework (ESMF)-based GEOS-5 AGCM and the new NCEP unified grid-point statistical interpolation (GSI) analysis scheme developed as a collaborative effort between NCEP and the GMAO.

MERRA supports NASA Earth science by synthesizing the current suite of research satellite observations in a climate data context (covering the period 1979-present), and by providing the science and applications communities with of a broad range of weather and climate data with an emphasis on improved estimates of the hydrological cycle.

MERRA products consist of a host of prognostic and diagnostic fields including comprehensive sets of cloud, radiation, hydrological cycle, ozone, and land surface diagnostics. A special collection of data files are designed to facilitate off-line forcing of chemistry/aerosol models. The model or native resolution of MERRA is ⅔ degree longitude by 1/2 degree latitude with 72 levels extending to 0.01 hPa. Analysis states and 2-dimensional diagnostics will be made available at the native resolution, while many of the three-dimensional diagnostics will be made available on a coarser 1.25° latitude °—1.25° longitude grid. Further information about MERRA and its status may be found at <http://gmao.gsfc.nasa.gov/research/merra/>

tracking control for observations, and to further improve the use of feedback data from reanalyses targeted especially for data providers/developers. Furthermore, the observational, reanalysis, and climate communities should take a coordinated approach to further optimizing the usefulness of reanalysis for climate. In fact, these recommendations have now been taken up by the WCRP Observations and Assimilation Panel (WOAP).

2.5.2 Modeling and Data Assimilation Issues

Spurious trends may also be introduced into the reanalyses by systematic errors in the models used to provide background estimates for data assimilation and by incomplete modeling of those systematic errors in the data assimilation algorithm. Atmospheric models include numerical representations of the primitive equations of motion along with parameterizations of small-scale processes such as radiation, turbulent fluxes, precipitation, *etc*. Model integrations begin with some estimate of the initial state, along with boundary values of solar radiation and sea surface temperature, and are integrated forward in time. While the first generation of global reanalyses (Table 2.1) had resolutions on the order of 100 to 200 km , the latest reanalysis efforts (NASA's Modern Era Retrospective-Analysis for Research and Applications or MERRA – see Box 2.2, and NOAA's Reanalysis and Reforecasts of the NCEP Climate Forecast System or CFSRR- see Box 2.3) have horizontal resolutions of about 50 km or less. Regional models have much finer resolution, currently approaching one kilometer, and time steps of seconds. Such improvements in resolution have improved representation of physical processes such as the strength and position of the storm tracks and thus have improved simulation of climate variability and reduced model bias.

However, despite these increases in resolution, many important physical processes still cannot be explicitly resolved in current global models, such as convection, cloud formation, and precipitation of both water and ice. Thus these processes must be parameterized, or estimated from other, presumably more accurately simulated, model variables. Inaccuracies in these parameterizations are a major source of uncertainty in numerical simulation of the atmosphere and are a cause of false trends, or bias, in atmospheric models. Of course, even if the initial conditions and parameterizations were nearly perfect, the presence of atmospheric instabilities (*e.g.*, Farrell, 1989; Palmer, 1988) will inevitably lead to model forecast errors.

Ocean models also include representations of the primitive equations, with parameterizations for processes such as mixing and sea ice physics. Ocean models exchange thermodynamic, radiative and momentum fluxes with the atmosphere. Horizontal resolution of current global ocean models is approaching 10 km, in order to resolve the complex geometry of the ocean basins and the oceanic mesoscale. However, despite this fine resolution such models still exhibit systematic errors, suggesting that the small horizontal and vertical scales upon which key processes such as vertical mixing, convection, and sea ice formation are still not being resolved (Smith *et al*., 2000).

In most analyses exchanges between ocean and atmosphere are one-way in the sense that the ocean reanalysis is controlled partly by atmospheric fluxes, while the atmospheric reanalysis is controlled partly by specified sea surface temperature. Thus the fluxes in the reanalyses computed for the ocean and for the atmosphere, which should be the same are in reality inconsistent. The alternative procedure of carrying out both reanalyses in a fully coupled atmosphere/ocean model would ensure consistency. But a consequence of doing this combined analysis is that the surface exchanges are less strongly constrained and thus initial efforts at a combined analysis are found to contain considerable systematic errors in both fluids (Collins *et al*., 2006; Delworth *et al*., 2006). Correcting these systematic errors will present a major challenge for future efforts to develop consistent and accurate atmosphere/ocean reanalyses. NCEP is currently carrying out the first coupled ocean-atmosphere reanalysis, with encouraging results, but it is too early to know the extent to which the fluxes and trends are reliable (Box 2.3).

The land surface component of an atmospheric model also provides fluxes of heat, water, and radiation at the atmosphere's lower boundary. The key difficulty in producing realistic land fluxes is the tremendous amount of spatial variability (relative to that found in the atmosphere or ocean) in the properties that control these fluxes – variability, for example, in topography, vegetation character, soil type, and soil moisture content. Such variability is very difficult to deal with for two reasons. First, given the spatial resolutions used for global reanalyses (now and in the foreseeable future), we cannot properly resolve the physical processes that control the land surface fluxes, so the small-scale processes must be parameterized. Second, even if the processes could be resolved, we lack the high resolution global measurements required for many of the relevant land properties.

Despite these limitations, land models have been used in numerous Land Data Assimilation System (LDAS) projects. The current LDAS approach is to drive regional or global arrays of land surface models with observations-based meteorological forcing (precipitation, radiation, *etc.*) rather than with forcing from an atmospheric model. This allows the land models to evolve their soil moisture and temperature states to (presumably) realistic values and to produce surface moisture and heat fluxes for diagnostic studies (Figure 2.21).

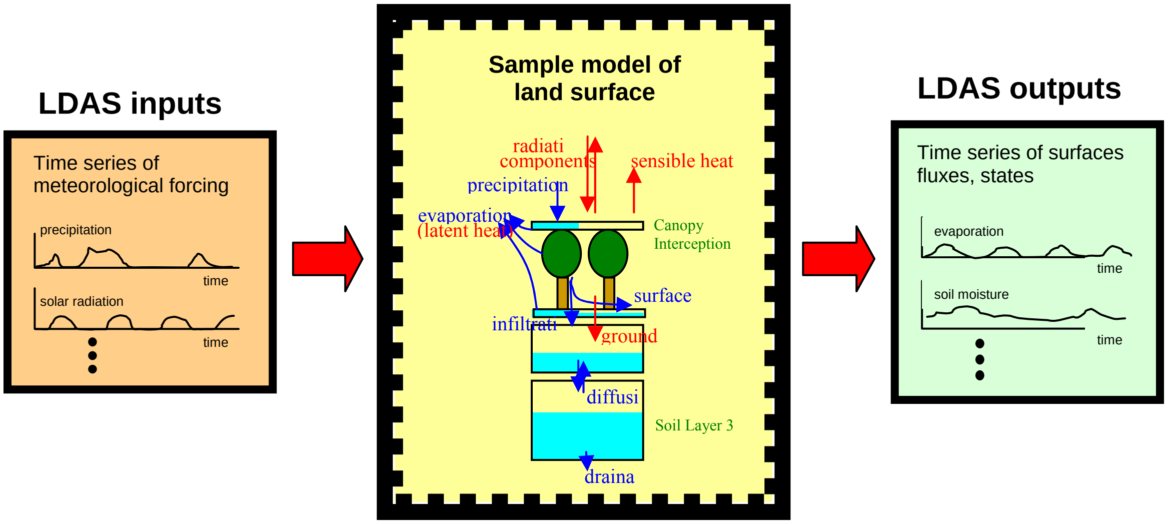

Figure 2.21. Schematic showing the inputs and outputs of a typical LDAS system.

A partial list of current LDAS projects is provided in Table 2.4. The LDAS framework is amenable to true assimilation, in which satellite- derived fields of soil moisture, snow, and temperature are incorporated into the gridded model integrations, using emerging techniques (*e.g.*, Reichle and Koster, 2005; Sun *et al*., 2004).

Table 2.4 A partial list of current Land Data Assimilation System (LDAS) projects.

Project	**Sponsor(s)**	**Spatial Domain**	**Unique Aspects**	**Reference**	**Project website**
GSWP-2	GEWEX	Global, 1^o	Separate datasets produced by at least 15 land models for the period 1986-1995	Dirmeyer *et al*. (2006)	http://www.iges.org/gswp2/
GLDAS	NASA, NOAA	Global, .25^o to ~2^o	Multiple land models; near-real-time data generation	Rodell *et al.* (2004)	http://ldas.gsfc.nasa.gov/
NLDAS	Multiple Institutions	Continental U.S., , 0.125^o	Multiple land models; near-real-time data	Mitchell *et al*. (2004)	http://ldas.gsfc.nasa.gov/

			generation		
ELDAS and ECMWF follow-on	European Commission	Europe, 0.2°	True data assimilation of air temperature and humidity in some versions	Van den Hurk (2002); Van den Hurk *et al.* (2008)	http://www.knmi.nl/samenw/eldas/

Data assimilation offers a general way to correct a background estimate of the state of the atmosphere, ocean, and land surface consistent with available observations (Kalnay, 2003; Wunsch, 2006). However, most current data assimilation algorithms make several assumptions for reasons of efficiency or from lack of information that limit their effectiveness. These assumptions include: 1) that any systematic trends, or biases, in the observation measurement or sampling have been identified and corrected, 2) that the forecast model is unbiased, and 3) that the error statistics such as the model forecast error have linear, Gaussian characteristics.

However, several changes can be made to ameliorate these assumptions. Systematic errors introduced by expansions of the observing system can be reduced by the procedure of repeating the reanalysis with a reduced, but more homogeneous data set, excluding for example, the satellite observations. An extreme version of this approach is to use only surface observations (Compo *et al.*, 2006). In that regard, atmospheric reanalysis schemes need to make better use of historical records of surface observations from land stations and marine platforms. This includes existing climate data sets (such as daily or monthly air temperature, pressure, humidity, precipitation, and cloudiness) that have already undergone extensive quality control for the purpose of climate variability and trend applications.

Box 2.3 Climate Forecast System Reanalysis and Reforecast Project (CFSRR)

The New Reanalysis and Reforecasts of the NCEP Climate Forecast System (CFSRR) is a major upgrade to the coupled atmosphere-ocean-land Climate Forecast System (CFS). This upgrade is being planned for Jan 2010 and involves changes to all components of the CFS including, the NCEP atmospheric Gridded Statistical Interpolation Scheme (GSI), the NCEP atmospheric Global Forecast System (GFS), the NCEP Global Ocean Data Assimilation System (GODAS) including the use of the new GFDL MOM4 Ocean Model, and the NCEP Global Land Data Assimilation System (GLDAS) including the use of a new NCEP Noah Land model.

There are two essential components to this upgrade: a new reanalysis of atmosphere, ocean, land and sea ice, and a complete reforecast of the new CFS. The new reanalysis will be conducted for the 31-year period (1979-2009). The reanalysis system includes an atmosphere with high horizontal (spectral T382, ~38 Km) and vertical (64 sigma-pressure hybrid levels) resolution, an ocean with 40 levels in the vertical to a depth of 4737 m and a horizontal resolution of 0.25 degree at the tropics, tapering to a global resolution of 0.5 degree northwards and southwards of 10N and 10S respectively, an interactive sea-ice model, and an interactive land model with 4 soil levels.

In addition to the higher horizontal and vertical resolution of the atmosphere, the key differences from the previous NCEP global reanalysis are that the guess forecast will be generated from a coupled atmosphere-ocean-land-sea ice system, and that radiance measurements from the historical satellites will be assimilated.

Nearly 1 Petabyte of data will be archived from the CFSRR, which will include hourly output at the highest resolution (0.5x0.5) for 37 atmospheric levels and 40 ocean levels. More information about CFSRR can be found at: <http://cfs.ncep.noaa.gov/cfsreanl/docs>

Systematic errors in the models may be explicitly accounted for and thus (potentially) corrected in the data assimilation algorithm, which then produces an analysis of both the model state and the model bias (*e.g.*, Dee and da Silva, 1998; Danforth *et al*., 2007). However, much additional work needs to be done to improve bias modeling. In addition to estimating and reducing bias, there is also a need to improve the representation of error covariances, and ultimately provide improved estimates of the uncertainties in all reanalysis products. New techniques such as the Ensemble Kalman Filter are being developed that are both economical and able to provide such estimates (*e.g.*, Tippett *et al*., 2003; Ott *et al*., 2004).

Looking ahead, a promising pathway for improved reanalyses is the development of coupled data assimilation systems along with methods to correct for the tendency of coupled models to develop bias. In this case the observed atmosphere, ocean, and land states are assimilated jointly into the atmosphere, ocean, and land components of a fully coupled climate system model. As already mentioned, the substantial bias in current coupled models makes this a significant challenge. Nevertheless, as we continue to improve our coupled models, this joint assimilation should ensure greater consistency of model states across the components because the states would be allowed to evolve together. For example, a satellite-based correction to a soil moisture value would be able to feed back on, and thereby potentially improve, overlying atmospheric moisture and temperature states. The overall result of coupled assimilation would presumably be a more reliable, and useful, reanalysis product. There are a number of efforts that are moving towards coupled data assimilation in the United States. These are focused primarily on developing more balanced initial conditions for the seasonal and longer forecast problem, and include the Climate Forecast System Reanalysis and Reforecast (CFSRR-see Box 2.3) Project at NCEP and an ensemble-based approach being developed at GFDL (Zhang *et al*., 2007). Also, the GMAO is utilizing the MERRA product (Box 2.2) and an ocean data assimilation system to explore data assimilation in a fully coupled climate model.

CHAPTER 2 REFERENCES

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Appendix 2.A Data Assimilation

Data assimilation is an exercise in the calculation of conditional probabilities in which short model forecasts are combined with observations to best estimate the state of, for example, the atmosphere. Because of limitations in model resolution and errors associated with parameterization of unresolved physical processes, and because of the chaotic behavior of the atmosphere, the accuracy of a forecast is described by a probability distribution. Similarly, the accuracy of observations is also described by a probability distribution. In data assimilation these probability distributions are combined to form conditional probabilities, which are simplified by assuming these distributions are Gaussian. The conditional probabilities are used to create a more accurate *analysis* than can be obtained solely from either the forecasts or the observations. The same approach can be applied to the ocean, land surface, or cryosphere.

Atmospheric data assimilation proceeds through a succession of *analysis cycles* of (typically) 6 hours. At the beginning of each cycle, a 6 hour model forecast is carried out starting from initial conditions of atmospheric pressure, temperature, humidity, and winds provided by the previous analysis cycle, with observed boundary conditions such as sea surface temperature and snow cover. At the end of each cycle all available current observations are quality controlled, and the differences between the observations and the model forecast of the same variables are computed (these differences are known as observational increments or innovations). The observations may include the same variables observed with different systems (*e.g.*, winds measured from airplanes or by following the movement of clouds). They may also include observations of variables that do not directly enter the forecast such as satellite radiances, observations of which contain information about both temperature and moisture.

If the evolving probability distributions of the model forecasts and observations were known then it is possible to construct an analysis that is optimal in the sense of minimizing the expected variance of the error (difference between the analysis of a variable and its true value). In practice we do not know the probability distributions. Also, we cannot solve the computational problem of minimizing the error variance for realistically complex systems. In order to address these twin problems a number of simplifying assumptions are needed. The observational increments are generally assumed to be Gaussian. With this assumption a cost function can be constructed whose minimization, which provides us with the optimal analysis, leads to the Kalman Filter equations. A more severe assumption that the probability distribution of the forecast errors is time-independent gives rise to the widely used and simpler three dimensional variational type of data assimilation (3DVAR). Four dimensional variational data assimilation (4DVAR) is a generalization of the cost function approach that allows the forecast initial conditions (or other control variables such as diffusive parameters) to be modified based on observations within a time window.

Despite the use of simplifying assumptions, the Kalman Filter and 4DVAR approaches still lead to vastly challenging computational problems. Efforts to reduce the magnitude of the computational problems and exploit physical understanding of the physical system have led to the development of Monte Carlo approaches known as Ensemble Kalman Filter (EnKF). EnKF methods, like 4DVAR, can be posed in such a way that the analysis at a given time can be influenced by future observations as well as present and past observations. This property of time symmetry is especially desirable in reanalyses since it allows the analysis at past times to benefit to some extent from future enhancements of the observing system.

Table 2.5 Characteristics of some existing global ocean model-based reanalyses of ocean climate (extracted from: http://www.clivar.org/data/synthesis/directory.php)

CNES, Météo France, CERFACS	OPA8.2, 2°x2°x31Lev (~0.5°x2° tropics) ERA40 forcing	Multivariate 3D-Var (OPAVAR) for T & S profiles	1962-2001	cerfacs.fr/globc/overview.html
ECMWF	HOPE, 1°x1°x29Lev (1/3°x1° tropics)	OI	1959-2006	ecmwf.int/products/forecasts/d/charts/ocean/reanalysis/
ECCO-GODAE	MITgcm 1°x1°	4DVAR	1992-2004	www.ecco-group.org
ECCO-JPL	MITgcm and MOM4 1°x1°x50 lev	Kalman filter and RTS smoother	1993-present	ecco.jpl.nasa.gov/external/
ECCO-SIO	1°x1°	4DVAR	1992-2002	ecco.ucsd.edu
ECCO2	MITgcm, 18kmx 18kmx50Lev	Green's functions	1992-present	
ENACT consortium			1962-2006	www.ecmwf.int/research/EU_projects/ENACT/
FNMOC/GODAE				www.usgodae.org
GECCO			1950-2000	www.ecco-group.org
GFDL			1960-2006	www.gfdl.noaa.gov/
UK Met Office GloSea	GloSea OGCM 1.25°x1.25°x40Lev (0.3°x1.25°tropics) daily ERA40 fluxes with corrected precipitation	OI	1962-1998	www.metoffice.gov.uk/research/seasonal/glosea.html
NASA Goddard GMAO	Poseidon, 1/3°x5/8°	MVOI, Ensemble KF	1993-pres	gmao.gsfc.nasa.gov
INGV	OPA8.2 2°x2°x31 lev (0.5°x2° tropics) ERA40 and operational ECMWF fluxes	Reduced Order MVOI with bivariate T and S EOFs	1962-pres	
MEXT K-7	MOMv3 1°x1°x36lev NCEP2 reanalysis, ISCCP data.	4D-VAR	1990-2000	www.jamstec.go.jp/frcgc/k7-dbase2/eng/
MERCATOR-3	OPA8.2 2°x2°x31lev (~0.5° meridional at the tropics)	Singular Evolutive Extended Kalman (SEEK) filter	1993-2001	www.mercator-ocean.fr/html/systemes_ops/psy3/index_en.html
JMA MOVE/MRI.COM			1949-2005	www.mri-jma.go.jp/Dep/oc/oc.html
NOAA/NCEP GODAS	MOMv3 1°x1°x40Lev (1/3°x1° tropics) NCEP Reanalysis2	3DVAR	1980-pres	www.cpc.ncep.noaa.gov/products/GODAS/
BoM, CSIRO, POAMA	ACOM2 (based on MOM2), 2°x2°x27Lev (0.5°x2° at high latitudes) ERA40	MVOI, ensemble KF	1980-2006	www.bom.gov.au/bmrc/ocean/JAFOOS/POAMA/
SODA	POP1.4, POP2.01, global ave 0.25°x0.25°x40Lev, ERA40, QuikSCAT	MVOI with evolving error covariances	1958-2005	www.atmos.umd.edu/~ocean/

Chapter 3. Attribution of the Causes of Climate Variations and Trends over North America during the Modern Reanalysis Period

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KEY FINDINGS

- Significant advances have occurred over the past decade in capabilities to attribute causes for observed climate variations and change.
- Methods now exist for establishing attribution for the causes of North American climate variations and trends due to internal climate variations and/or changes in external climate forcing.

Annual, area-average change since 1951 across North America show:

- Seven of the warmest ten years for annual surface temperatures since 1951 have occurred in the last decade (1997 to 2006).

- The 56-year linear trend (1951 to 2006) of annual surface temperature is +0.90°C +/-0.1°C.
- Virtually all of the warming since 1951 has occurred after 1970.
- More than half of the warming is *likely* the result of anthropogenic forcing.
- Changes in ocean temperatures *likely* explain a substantial fraction of the anthropogenic warming of North America.
- There is no discernible trend in precipitation since 1951, in contrast to trends observed in extreme precipitation events (CCSP, in press).

Spatial variations in annual-average change since 1951 across North America show:

- Observed surface temperature change has been largest over northern and western North America, with up to +2°C/56 years warming over Alaska, the Yukon Territories, Alberta, and Saskatchewan.
- Observed surface temperature change has been least over the southern United States and eastern Canada, where no significant trends have occurred.
- There is *very high* confidence that changes in free atmospheric circulation have occurred based upon reanalysis data, and that these circulation changes are the *likely* physical basis for much of the spatial variations in surface temperature change over North America, especially during winter.
- The spatial variations in surface temperature change over North America are *unlikely* the result of anthropogenic forcing alone.

- The spatial variations in surface temperature change over North America are very *likely* influenced by variations in global sea surface temperatures through the effects of the latter on atmospheric circulation, especially during winter.

Spatial variations of seasonal average change since 1951 across the United States show:

- Six of the warmest ten summers and winters for conterminous United States averaged surface temperatures since 1951 have occurred in the last decade (1997 to 2006).
- During summer, surface temperatures have warmed most over western states, with insignificant change between the Rocky and Appalachian Mountains. During winter, surface temperatures have warmed most over northern and western states, with insignificant change over the central Gulf of Mexico, and Maine.
- The spatial variations in summertime surface temperature change are *unlikely* the result of anthropogenic forcing alone.
- The spatial variations and seasonal differences in precipitation change are *unlikely* the result of anthropogenic forcing alone.
- Some of the spatial variations and seasonal differences in precipitation change and variations are *likely* the result of regional variations in sea surface temperatures.

With respect to abrupt climate change over North America in the reanalysis period:

- Current reanalysis data extends back until only the middle of the last century, posing limitations for detecting rapid climate shifts and distinguishing them from quasi-cyclical variations.

For droughts:

- It is *unlikely* that a systematic change in either the frequency or area coverage of severe drought occurred over the conterminous United States during the past half-century.
- It is *very likely* that short-term (monthly-to-seasonal) severe droughts that have impacted North America during the past half-century are mostly due to atmospheric variability, in some cases amplified by local soil moisture conditions.
- It is *likely* that sea surface temperature anomalies have been important in forcing long-term (multi-year) severe droughts that have impacted North America during the past half-century.
- It is *likely* that anthropogenic warming has increased the severity of both short-term and long-term droughts over North America in recent decades.

INTRODUCTION

Increasingly, climate scientists are being asked to go beyond descriptions of *what* the current climate conditions are and how they compare with the past, to also explain *why* climate is evolving as observed; that is, to provide attribution of the causes for observed climate variations and change.

Today, a fundamental concern for policy-makers is to understand the extent to which anthropogenic factors and natural climate variations are responsible for the observed evolution of climate. A central focus for such efforts, as articulated in the IPCC assessments, has been to establish the cause, or causes, for global-mean temperature increases over roughly the past century. However, requests for climate attribution far transcend this single variable, with notable interest in explaining regional variations and the causes for high-impact climate events, such as the recent multi-year drought in the western United States and the record setting 2006 United States warmth. For many decision makers who must assess potential impacts and management options, a particularly important question is: What are and how well do we understand the causes for regional and seasonal differences in climate variations and trends? For example, is the source for the recent drought in the western United States due mainly to factors internal to the climate system, in which case a return toward previous climate conditions might be anticipated, or is it rather a manifestation of a longer-term trend toward increasing aridity in the region that is driven primarily by anthropogenic forcing? Why do some droughts last longer than others? Such examples illustrate that to support informed decision making, the capability to attribute causes for past and current climate conditions can be of fundamental importance.

The recently completed IPCC Fourth Assessment Report (AR4) from Working Group I contains a full chapter devoted to the topic “Understanding and Attributing Climate Change” (IPCC, 2007a). In the present chapter, we have attempted to minimize overlap with the IPCC report by focusing on a subset of questions of particular interest to the United States public, decision makers, and policymakers that may not have been covered in detail (or in some cases, at all) in the IPCC report. The specific emphasis here is on our present ability – or inability – to attribute the causes for observed climate variations and change over North America. For a more detailed discussion of attribution, especially for other regions and at the global scale, the interested reader is referred to chapter 9 of the AR4 Working Group I report.

Figure 3.1 illustrates methods and tools used in climate attribution. The North American map (right side) shows an observed surface condition whose causes are sought. A roadmap for attribution involves the systematic probing of cause-effect relationships. Plausible forcings are identified along the top of Figure 3.1 (brown oblongs), and arrows illustrate connections among these and also pathways for explaining the observed condition.

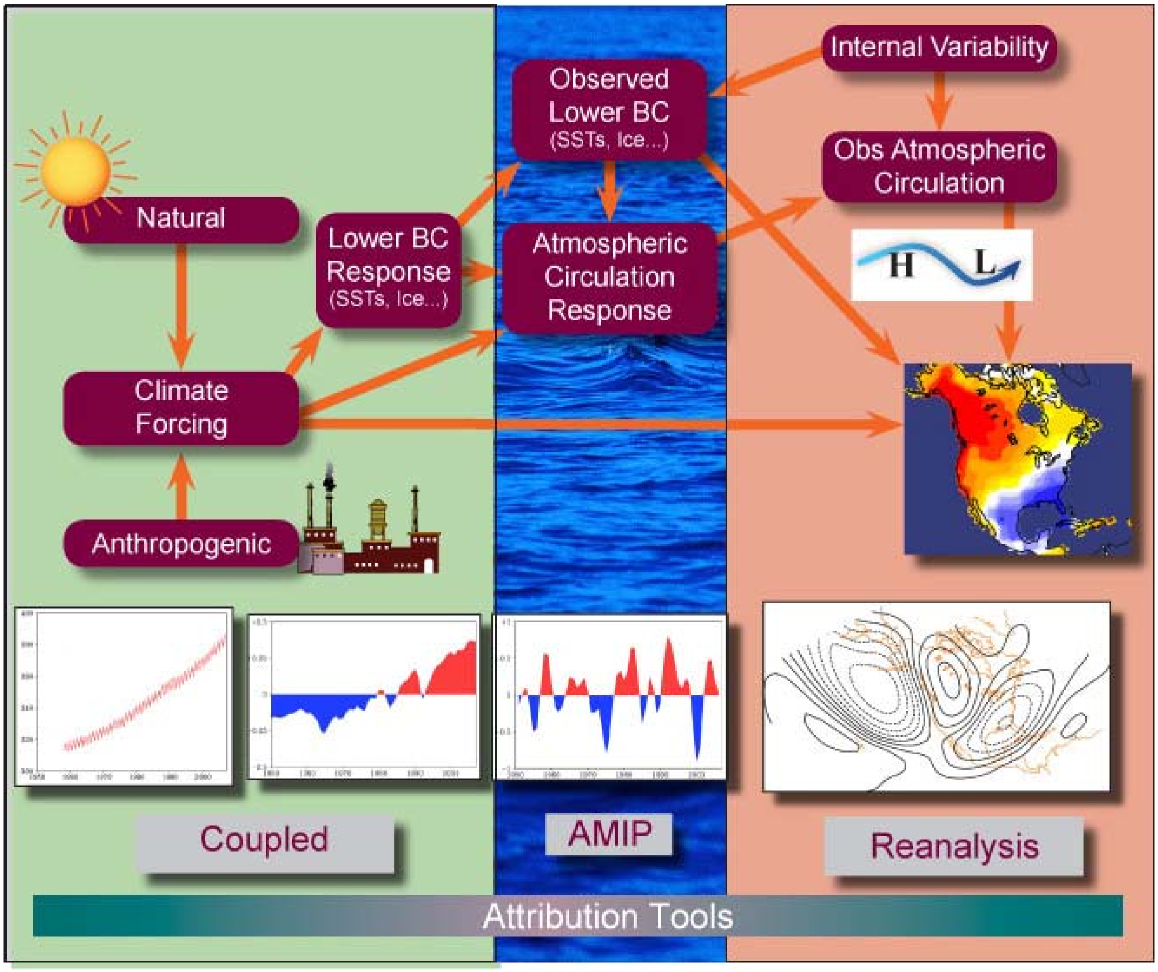


Figure 3.1 Schematic illustration of the data sets and modeling strategies for performing attribution. The right-side map displays a North American climate condition whose origin is in question. Various candidate causal mechanisms are illustrated in the right-to-left sequences of figures, together with the attribution tool. Listed above each in brown oblongs is a plausible cause that could be assigned to the demonstrated mechanism depending upon the diagnosis of forcing-response relationships derived from attribution methods. The efficacy of the first mechanism is tested, often empirically, by determining consistency with patterns of atmospheric variability, such as the teleconnection processes identifiable from reanalysis data. This step places the current condition within a global and historical context. The efficacy of the second mechanism tests the role of boundary forcings, most often with atmospheric models (AMIP). The efficacy of the third mechanism tests the role of external forcings, most often with coupled ocean-atmosphere models. The processes responsible for the climate condition in question may, or may not, involve teleconnections, but may result from local changes in direct radiative forcing or other near-surface forcing such as from land surface anomalies. The lower panels illustrate representative process: from left-to-right; time-evolving atmospheric carbon dioxide at Mauna Loa, the multi-decadal warming trend in tropical west Pacific-Indian Ocean warm pool SSTs, the yearly SST variability over the tropical east Pacific due to ENSO, the atmospheric pattern over the North Pacific/ North America referred to as the PNA teleconnection.

The attribution process begins by examining conditions of atmospheric circulation that coincide with the North American surface climate anomaly. It is possible, for instance, that the surface condition evolved in concert with a change in the tropospheric jet stream, such as accompanies the Pacific-North American pattern (Chapter 2). Reanalysis data is the essential tool for this purpose because it provides a global description of the state of the tropospheric climate that is physically consistent in space and time. Reanalysis as an attribution tool, however, only offers a connection between the surface and tropospheric climate without necessarily *explaining* its causes.

Additional tools are often needed to explain the circulation pattern itself. Is it, for instance, due to chaotic internal atmospheric variations, or is it related to forcing external to the atmosphere (*e.g.*, sea surface temperature forcing, or radiative forcing)? The middle column in Figure 3.1 illustrates the common approach used to assess the forcing-response associated with Earth's lower boundary conditions, in particular sea surface temperatures. The principal tool is atmospheric general circulation models forced with the specified history of surface boundary conditions (Gates, 1992). Reanalysis would continue to be important in this stage of attribution in order to evaluate the suitability of the models as an attribution tool, including the realism of simulated circulation variability (Box 3.1).

In the event that diagnosis of the AMIP simulation fails to confirm a role for Earth's lower boundary conditions, then two plausible explanations for the circulation (and its associated North American surface condition) remain. One is that it was unforced, being instead due to chaotic atmospheric variability. Reanalysis data would be useful to determine whether the circulation state was within the scope of known variations during the reanalysis record. Alternatively, external natural (*e.g.*, volcanic and solar) or external anthropogenic perturbations may directly have caused the responsible circulation pattern. Coupled ocean-atmosphere climate models would be used to explore the forcing-response relationships involving such external forcings. Illustrated by the left column, coupled models have been widely employed in the reports of the IPCC. Here again, reanalysis is important for assessing the suitability of this attribution tool, including the realism of simulated ocean-atmosphere variations such as El Niño and accompanying atmospheric teleconnections that influence North American surface climate (Box 3.1).

In the event that diagnosis of the AMIP simulations confirms a role for Earth's lower boundary conditions, it becomes important to explain the cause for the boundary condition itself. Comparison of the observed sea surface temperatures with coupled model simulations would be the principal approach. If anthropogenically forced coupled models fail to yield the observed boundary conditions, then they may be attributed to chaotic intrinsic coupled ocean-atmosphere variations. If instead coupled models replicate the observed boundary conditions, this establishes a consistency with external forcing as an ultimate cause. (It is also necessary to confirm that the coupled models also generate the atmospheric circulation patterns; that is, to demonstrate that the models got the result for the correct physical reason).

The schematic illustrates basic approaches applied in the following sections of Chapter 3. It is evident that a physically-based scientific interpretation for the causes of a climate condition requires accurately measured and analyzed features of the time and space characteristics of atmospheric circulation and surface conditions. In addition, it relies heavily upon the use of climate models to test candidate cause-effect relations. Reanalysis is essential for both components of such attribution science.

While this Chapter considers the approximate period covered by modern reanalyses (roughly 1950 to the present), data sets other than reanalyses such as gridded surface station analyses of temperature and precipitation are also used. In fact, the surface condition illustrated in Figure 3.1 are generally derived from such data sets, and these are extensively employed to describe various key features of the recent North American climate variability in Chapter 3. These, together with modern reanalysis data, provide a necessary historical context against which the uniqueness of current climate conditions both at Earth's surface and in the free atmosphere can be assessed.

3.1 WHAT IS CLIMATE ATTRIBUTION, AND WHAT ARE THE SCIENTIFIC METHODS USED FOR ESTABLISHING ATTRIBUTION?

3.1.1 What is Attribution?

Climate attribution is a scientific process for establishing the principal causes or physical explanation for observed climate conditions and phenomena. Within its reports, the IPCC states that "attribution of causes of *climate change* is the process of establishing the most likely causes for the detected change with some level of confidence." As noted in the

Introduction, the definition is expanded herein to include attribution of the causes of observed *climate variations* that may not be unusual in a statistical sense but for which great public interest exists because they produce profound societal impacts.

It is useful at the outset to outline some general classes of mechanisms that may produce climate variations or change. One important class is *external forcing*, which contains both *natural* and *anthropogenic* sources. Examples of natural external forcing include solar variability and volcanic eruptions. Examples of anthropogenic forcing are changing concentrations of greenhouse gases and aerosols, and land cover changes produced by human activities. A second class involves *internal mechanisms* within the climate system that can produce climate variations manifesting themselves over seasons, decades, and longer. Internal mechanisms include processes that are due primarily to interactions within the atmosphere as well as those that involve coupling of the atmosphere with various components of the climate system. Climate variability due to purely internal mechanisms is often called *internal variability*.

For attribution to be established, the relationship between the observed climate state and the proposed causal mechanism needs to be demonstrated, and alternative explanations need to be determined as unlikely. In the case of attributing the cause of a climate condition to internal variations, for example, due to El Niño-related tropical east Pacific sea surface conditions, the influence of alternative modes of internal climate variability must also be assessed. Before attributing a climate condition to anthropogenic forcing, it is important to determine that the climate condition was unlikely to have resulted from natural external forcing or internal variations alone.

Attribution is most frequently associated with the process of explaining a *detected change*. In particular, attribution of anthropogenic climate change - the focus of the IPCC reports (Houghton *et al.*, 1996; Houghton *et al.*, 2001; IPCC, 2007a) - has the specific objective of explaining a detected climate change that is significantly different from that which could be expected from natural external forcing or internal variations of the climate system. According to the Third Assessment Report (TAR), the attribution requirements for a detected change are: (1) a demonstrated consistency with a combination of anthropogenic and natural external forcings, and (2) an inconsistency with "alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings" (Houghton *et al.*, 2001).

3.1.2 How is Attribution Performed?

The methods used for attributing the causes for observed climate conditions depend on the specific problem or context. To establish the cause requires identifying candidate forcings, determining the response produced by such forcings, and determining the agreement between the forced response and the observed condition. It is also necessary to demonstrate that the observed climate condition is unlikely to have originated from other forcing mechanisms.

The methods for signal identification, as discussed in more detail below, involve both empirical analysis of past climate relationships and experiments with climate models in which forcing-response relations are evaluated. Similarly, estimates of internal variability can be derived from the instrumental records of historical data including reanalyses and from simulations performed by climate models in the absence of the candidate forcings. Both empirical and modeling approaches have limitations. The former is hampered by the relatively short duration of the climate record, the confounding of influences from various forcing mechanisms, and by possible non-physical inhomogeneities in the climate record that can result from changing monitoring techniques and analysis procedures (see Chapter 2 for examples of non-physical trends in precipitation owing to shifts in reanalysis methods). The climate models are hampered by uncertainties in the representation of physical processes and by coarse spatial resolution (currently on the order of several hundred kilometers) that can lead to model biases. In each case, the identified signal (forcing-response relationship) must be robust to these uncertainties. This includes demonstrating that an empirical analysis is both physically meaningful and is robust to sample size, and that a numerical result is replicated when using different climate models. Best attribution practices employ combinations of empirical and numerical approaches using multiple climate models, to minimize the effects of possible biases resulting from a single line of approach. Following this approach, Table 3.1 and Table 3.2 lists the observational and model data sets used to generate analyses in Chapter 3.

Table 3.1 Acronyms of climate models referenced in this Chapter. All 19 models performed simulations of 20th century climate change ("20CEN") as well as the 720 ppm stabilization scenario (SRESA1B) in support of the IPCC Fourth Assessment Report. The ensemble size "ES" is the number of independent realizations of the 20CEN experiment that were analyzed here.

	MODEL ACRONYM	COUNTRY	INSTITUTION	ES
1	**CCCma-CGCM3.1(T47)**	**Canada**	**Canadian Centre for Climate Modelling and Analysis**	**1**
2	**CCSM3**	**United States**	**National Center for Atmospheric Research**	**6**
3	**CNRM-CM3**	**France**	**Météo-France/Centre National de Recherches Météorologiques**	**1**
4	**CSIRO-Mk3.0**	**Australia**	**CSIRO[1] Marine and Atmospheric Research**	**1**
5	**ECHAM5/MPI-OM**	**Germany**	**Max-Planck Institute for Meteorology**	**3**
6	**FGOALS-g1.0**	**China**	**Institute for Atmospheric Physics**	**1**
7	**GFDL-CM2.0**	**United States**	**Geophysical Fluid Dynamics Laboratory**	**1**
8	**GFDL-CM2.1**	**United States**	**Geophysical Fluid Dynamics Laboratory**	**1**
9	**GISS-AOM**	**United States**	**Goddard Institute for Space Studies**	**2**
10	**GISS-EH**	**United States**	**Goddard Institute for Space Studies**	**3**
11	**GISS-ER**	**United States**	**Goddard Institute for Space Studies**	**2**
12	**INM-CM3.0**	**Russia**	**Institute for Numerical Mathematics**	**1**
13	**IPSL-CM4**	**France**	**Institute Pierre Simon Laplace**	**1**
14	**MIROC3.2(medres)**	**Japan**	**Center for Climate System Research / NIES[2] / JAMSTEC[3]**	**3**
15	**MIROC3.2(hires)**	**Japan**	**Center for Climate System Research / NIES[2] / JAMSTEC[3]**	**1**
16	**MRI-CGCM2.3.2**	**Japan**	**Meteorological Research Institute**	**5**
17	**PCM**	**United States**	**National Center for Atmospheric Research**	**4**
18	**UKMO-HadCM3**	**United Kingdom**	**Hadley Centre for Climate Prediction and Research**	**1**
19	**UKMO-HadGEM1**	**United Kingdom**	**Hadley Centre for Climate Prediction and Research**	**1**

[1] CSIRO is the Commonwealth Scientific and Industrial Research Organization.
[2] NIES is the National Institute for Environmental Studies.
[3] JAMSTEC is the Frontier Research Center for Global Change in Japan.

Table 3.2 Data sets utilized in the report. The versions of these data used in this report include data through December 2006. The web sites listed below provide URLs to the latest versions of these data sets, which may incorporate changes made after December 2006.

CRU HadCRUT3v Climatic Research Unit of the University of East Anglia and the Hadley Centre of the UK Met Office
http://www.cru.uea.uk/cru/data/temperature/

NOAA Land/Sea Merged Temperature NOAA's National Climatic Data Center (NCDC)
http://www.ncdc.noaa.gov/oa/climate/research/anomalies/

NASA Land+Ocean Temperature NASA's Goddard Institute for Space Studies (GISS)
http://data.giss.noaa.gov/gistemp/

NCDC Gridded Land Temperature NOAA's National Climatic Data Center (NCDC)
Gridded Land Precipitation
http://www.ncdc.noaa.gov/oa/climate/research/ghcn/

NCDCdiv Contiguous U.S. Climate Division Data (temperature and precipitation)
http://www.ncdc.noaa.gov/oa/climate/onlineprod/

PRISM Spatial Climate Gridded Data Sets (temperature and precipitation) Oregon State University's Oregon Climate Service (OCS)
http://prism.oregonstate.edu

CHEN Global Land Precipitation NOAA's Climate Prediction Center (CPC)
http://www.cpc.noaa.gov/products/precip/

GPCC Global Gridded Precipitation Analysis Global Precipitation Climatology Centre (GPCC)
http://www/dwd/de/en/FundE/Klima/KLIS/int/GPCC/

CMIP3 CMIP3 World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset
http://www-pcmdi.llnl.gov/ipcc/

Reanalysis NCEP50 National Centers for Environmental Prediction (NCEP), NOAA, and the National Center for Atmospheric Research (NCAR)
http://dss.ucar.edu/pub/reanalysis/data_usr.html/

ECHAM4.5 ECHAM4.5
http://iridl.ldeo.columbia.edu/SOURCES/.IRI/.FD/.ECHAM4p5/.History/.MONTHLY

NASA/NSIPP Runs

The specific attribution method can also differ according to the forcing-response relation being probed. As discussed below, three methods have been widely employed. These consider different hierarchical links in causal relationships as illustrated in the schematic Figure 3.1 as discussed in Section 3.1.2.1: (i) climate conditions rising from mechanisms internal to the atmosphere, (ii) climate conditions forced from changes in atmospheric lower boundary conditions (for example, changes in ocean or land surface conditions), and (iii) climate conditions forced externally, whether natural or anthropogenic. Note that in some cases, more than one of these links, or pathways, can be involved. For example, changes in greenhouse gas forcing may induce changes in the ocean component of the climate system. These ocean conditions can then force a response in the atmosphere that leads to regional temperature or precipitation changes.

3.1.2.1 Signal determination

i) Attribution to internal atmospheric variations

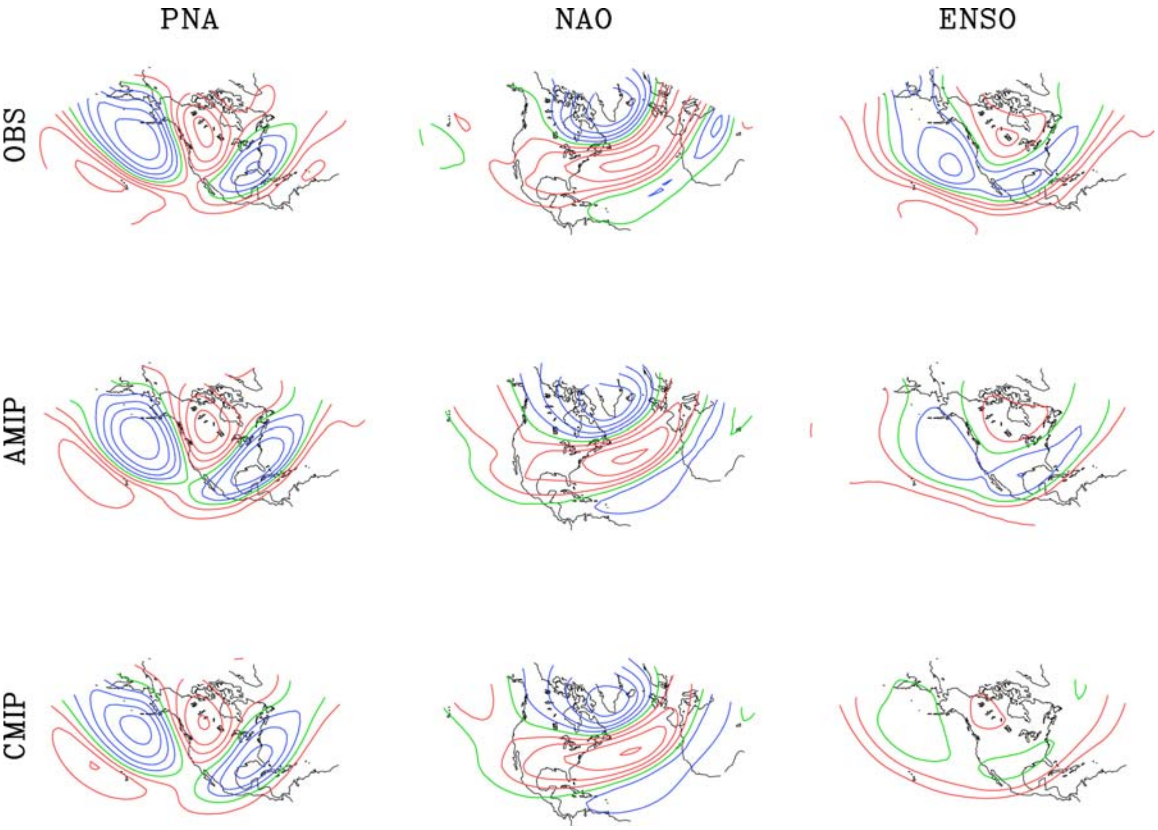
Pioneering empirical research, based only on surface information, discovered statistical linkages between anomalous climate conditions that were separated by continents and oceans (Walker and Bliss, 1932), structures that are referred to today as teleconnection patterns. The North Atlantic Oscillation (NAO); a see-saw in anomalous pressure between the subtropical North Atlantic and the Arctic, and the Pacific-North American (PNA) pattern; a wave pattern of anomalous climate conditions arching across the North Pacific and North American regions, are of particular relevance to understanding North American climate variations. Chapter 2 has illustrated the use of reanalysis data to diagnose the tropospheric wintertime atmospheric circulations associated with a specific phase of the PNA and NAO patterns, respectively. They each have widespread impacts on North American climate conditions as revealed by station-based analyses of surface temperature and precipitation anomalies, and the reanalysis data of free atmospheric conditions provides the foundation for a physical explanation of the origins of those fingerprints. The reanalysis data are also used to validate the realism of atmospheric circulation in climate models, as illustrated in Box. 3.1.

BOX 3.1 Assessing Model Suitability

A principal tool for attributing the causes of climate variations and change involves climate models. For instance, atmospheric models using specified sea surface temperatures are widely used to assess the impact of El Niño on seasonal climate variations. Coupled ocean-atmosphere models using specified atmospheric chemical constituents are widely used to assess the impact of greenhouse gases on detected changes in climate conditions. One prerequisite for the use of models as tools is their capacity to simulate the known leading patterns of atmospheric (and for the coupled models, oceanic) modes of variations. Realism of the models enhances confidence in their use for probing forcing-response relationships, and it is for this reason that an entire chapter of the IPCC Fourth Assessment Report is devoted to evaluation of the models for simulating known features of large-scale climate variability. That report emphasizes the considerable scrutiny and evaluations under which these models are being placed, making it "less likely that significant model errors are being overlooked". *Reanalysis data of global climate variability of the past half-century provide valuable benchmarks against which key features of model simulations can be meaningfully assessed.*

The figure below illustrates a simple use of reanalysis for validation of models that are employed for attribution elsewhere in this report. Chapter 8 of the Working Group I report of IPCC AR4 and the references therein provide numerous additional examples of validation studies of the IPCC coupled models that are used in this SAP. Shown are the leading winter patterns of atmospheric variability, discussed previously in Chapter 2 (Figures 2.8 and 2.9), that have strong influence on North American climate. These are the Pacific-North American pattern (left), the North Atlantic Oscillation pattern (middle), and the El Niño/Southern Oscillation pattern (right). The spatial expressions of these patterns is depicted using correlations between observed (simulated) indices of the PNA, NAO, and ENSO with wintertime 500 hPa geopotential heights derived from reanalysis (simulation) data for 1951 to 2006. Both atmospheric (middle) and coupled ocean-atmospheric (bottom) models realistically simulate the phase and spatial scales of the observed (top) patterns over the Pacific-North American domain. The correlations within the PNA and NAO centers of action are close to those observed indicating the fidelity of the models in generating these atmospheric teleconnections. The ENSO correlations are appreciably weaker in the models than in reanalysis. This is in part due to averaging over multiple models and multiple realizations of the same model. It \perhaps also indicates that the tropical-extratropical interactions in these models is weaker than observed, and for the CMIP runs it may also indicate weaker ENSO sea surface temperature variability. These circulation patterns are less pronounced during summer, at which time climate variations become more dependant upon local processes (*e.g.*, convection and land-surface interaction) which poses a greater challenge to climate models.

More advanced applications of reanalysis data to evaluate models include budget diagnoses that test the realism of physical processes associated with climate variations, frequency analysis of the time scales of variations, and multi-variate analysis to assess the realism of coupling between surface and atmospheric fields. It should be noted that despite the exhaustive evaluations that can be conducted, model assessments are not always conclusive about their suitability as an attribution tool. First, the tolerance to biases in models needed to produce reliable assessment of cause-effect relationships is not well understood. It is partly for this reason that large multi-model ensemble methods are employed for attribution studies in order to reduce the random component of biases that exist across individual models. Second, even when known features of the climate system are judged to be realistically simulated in models, there is no assurance that the modeled response to increased greenhouse gas emissions will likewise be realistic under future scenarios. Therefore attribution studies (IPCC, chapter 9) compare observed with climate model simulated change because such sensitivity is difficult to evaluate from historical observations.



Box Figure B.3-1 Temporal correlation between winter season (December, January, February) 500 hPa geopotential heights and indices of the leading patterns of Northern Hemisphere climate variability: Pacific-North American (PNA, left), North Atlantic Oscillation (middle), and El Niño/Southern Oscillation (ENSO, right) circulation patterns. The ENSO index is based on equatorial Pacific SSTs averaged 170°W-120°W, 5°N-5°S, and the PNA and NAO indices based on averaging heights within centers of maximum observed height variability following Wallace and Gutzler (1981). Assessment period is 1951 to 2006: observations based on reanalysis data (top), simulations based on atmospheric climate models forced by observed specified sea surface temperature variability (middle), and coupled ocean-atmosphere models forced by observed greenhouse gas, aerosol, solar and volcanic variability (bottom). AMIP comprised of 2 models and 33 total simulations. CMIP comprised of 19 models and 19 total simulations. Positive (negative) correlations in red (blue) contours.

***********END BOX 3.1 *****************

Observations of atmospheric circulation patterns in the free atmosphere fueled theories of the dynamics of these teleconnections, clarifying the origins for their regional surface impacts (Rossby, 1939). The relevant atmospheric circulations represent fluctuations in the semi-permanent positions of high and low pressure centers, their displacements being induced by a variety of mechanisms including anomalous atmospheric heating (*e.g.*, due to changes in tropical rainfall patterns), changes in wind flow over mountains, the movement and development of weather systems (*e.g.*, along their storm tracks across the oceans), and other processes (Wallace and Guzzler, 1981; Horel and Wallace, 1981; see Glantz *et al.*, 1991 for a review of the various mechanisms linking worldwide climate anomalies). The PNA and NAO patterns are now recognized as representing preferred structures of extratropical climate variations that are readily triggered by internal atmospheric mechanisms and also by surface boundary forcing, especially from ocean sea surface temperatures (Hoskins and Karoly, 1981; Horel and Wallace, 1981; Simmons *et al.*, 1983).

As indicated in Chapter 2, these and other teleconnection patterns are readily identifiable in the monthly and seasonal averages of atmospheric circulation anomalies in the free atmosphere using reanalysis data. Reanalysis data has also been instrumental in understanding the causes of teleconnection patterns and their North American surface climate impact (Feldstein 2000, 2002; Thompson and Wallace, 1998, 2000a,b). The ability to assess the relationships between teleconnections and their surface impacts provides an important foundation for attribution - North America climate variations are often due to particular atmospheric circulation patterns that connect climate anomalies over distance regions of the globe. Such a connection is illustrated schematically in Figure 3.1.

ii) Attribution to surface boundary forcing

In some situations, teleconnections including those described above are a forced response to anomalous conditions at the Earth's surface. Under such circumstances higher order attribution statements that go beyond the statement of how recurrent features of the atmospheric circulation affect North American surface climate are feasible, and provide an explanation for the cause for the circulation itself.

A particular example is the atmospheric response to tropical Pacific sea surface temperature anomalies, which takes the form of a PNA-like pattern having significant impacts on North American climate especially in the winter and spring seasons. It should be noted, however, that other surface forcings, such as related to sea ice and soil moisture conditions, can also cause appreciable climate anomalies, though their influence is more local and does not usually involve teleconnections.

Jacob Bjerknes (1966, 1969) demonstrated that a surface pressure sea-saw between the western and eastern tropical Pacific (now known as the Southern Oscillation) was linked with the occurrence of anomalous equatorial Pacific SST anomalies referred to as El Niño. This so-called El Niño-Southern Oscillation (ENSO) phenomenon was discovered to be an important source for year-to-year North American climate variation, with recent examples being the strong El Niño events of 1982 to 1983 and 1997 to 1998 whose major meteorological consequences over North America included flooding and storm damage over a wide portion of the western and southern United States and unusually warm winter temperatures over the northern United States (Rasmusson and Wallace, 1983). The cold phase of the cycle, referred to by La Niña, also has major impacts on North America, in particular an enhanced drought risk across the southern and western United States (Ropelewski and Halpert, 1986; Cole *et al.*, 2002)

The impacts of El Niño on North American climate have been extensively documented using both historical data and with sensitivity experiments using atmospheric climate models forced with specified SST conditions observed during El Niño (see review by Trenberth *et al.*, 1998). Figure 3.2 illustrates the observed wintertime tropospheric circulation pattern during El Niño events of the last half century based on reanalysis data, and the associated North American surface signatures in temperature and precipitation. Reanalysis data is of sufficient fidelity to distinguish between the characteristic circulation pattern of the PNA (Figure 2.8) and that induced by El Niño - the latter having more widespread high pressure over Canada. Surface temperature features consist more of a north-south juxtaposition of warm-cold over North America during El Niño, as compared to the west-east structure associated with the PNA. The capacity to observe such distinctions is vital when conducting attribution because particular climate signatures indicate different candidate causes.

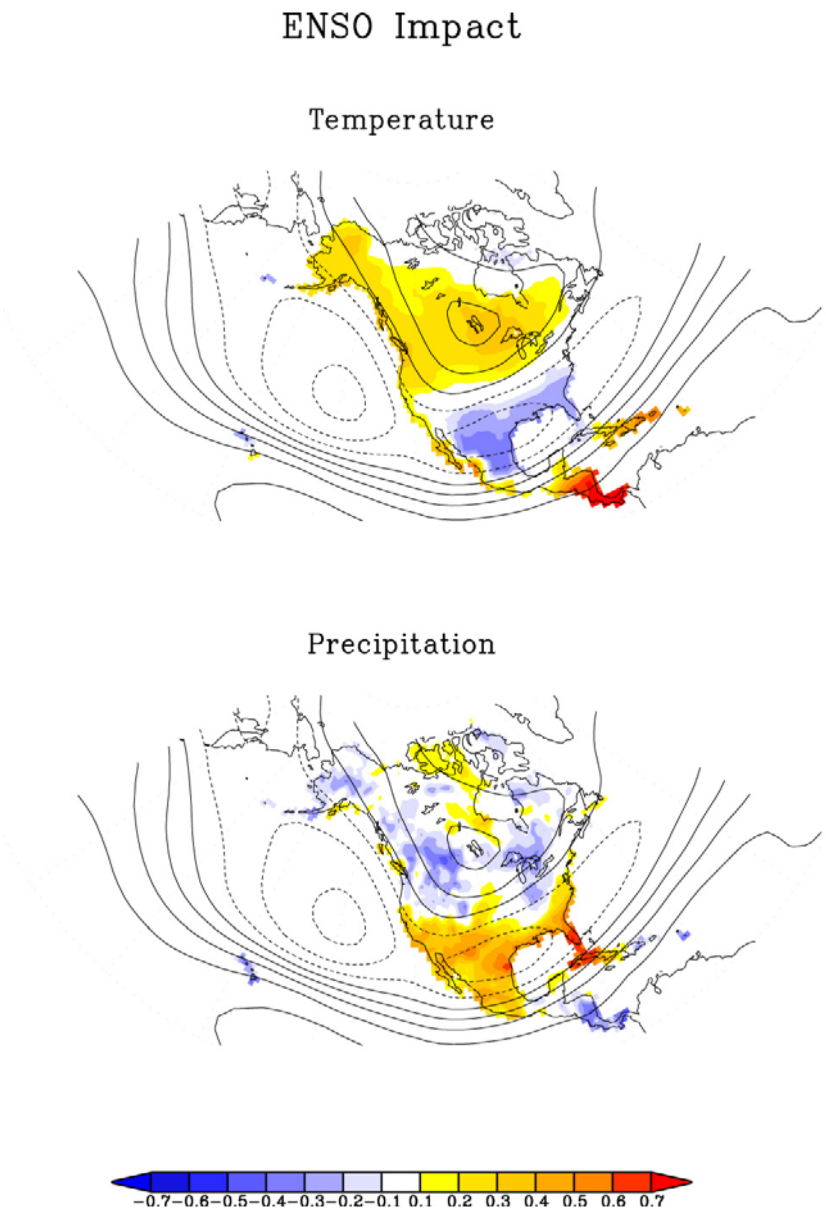


Figure 3.2 The correlation between an SST index of ENSO and 500 mb height field (contours). The shading indicates the correlations between ENSO index and the surface temperature (top panel) and the precipitation (bottom panel). The 500mb height is from the NCEP/NCAR R1 reanalysis. The surface temperature and precipitation are from independent observational data sets. The correlations are based on seasonal mean winter (December-January-February) data for the period 1951 to 2006. The contours with negative correlation are dashed.

The use of climate models subjected to specified SSTs has been essential for elucidating the role of oceans in climate, and such tools are now extensively employed in seasonal climate forecast practices. The atmospheric models are often subjected to realistic globally complete, monthly evolving SSTs (so-called AMIP experiments (Atmospheric Model Intercomparison Project; Gates, 1992)) or to regionally confined idealized SST anomalies in order to explore specific cause-effect relations. These same models have also been used to assess the role of sea ice and soil moisture conditions on climate. The process of forcing a climate model is discussed further in Box 3.2.

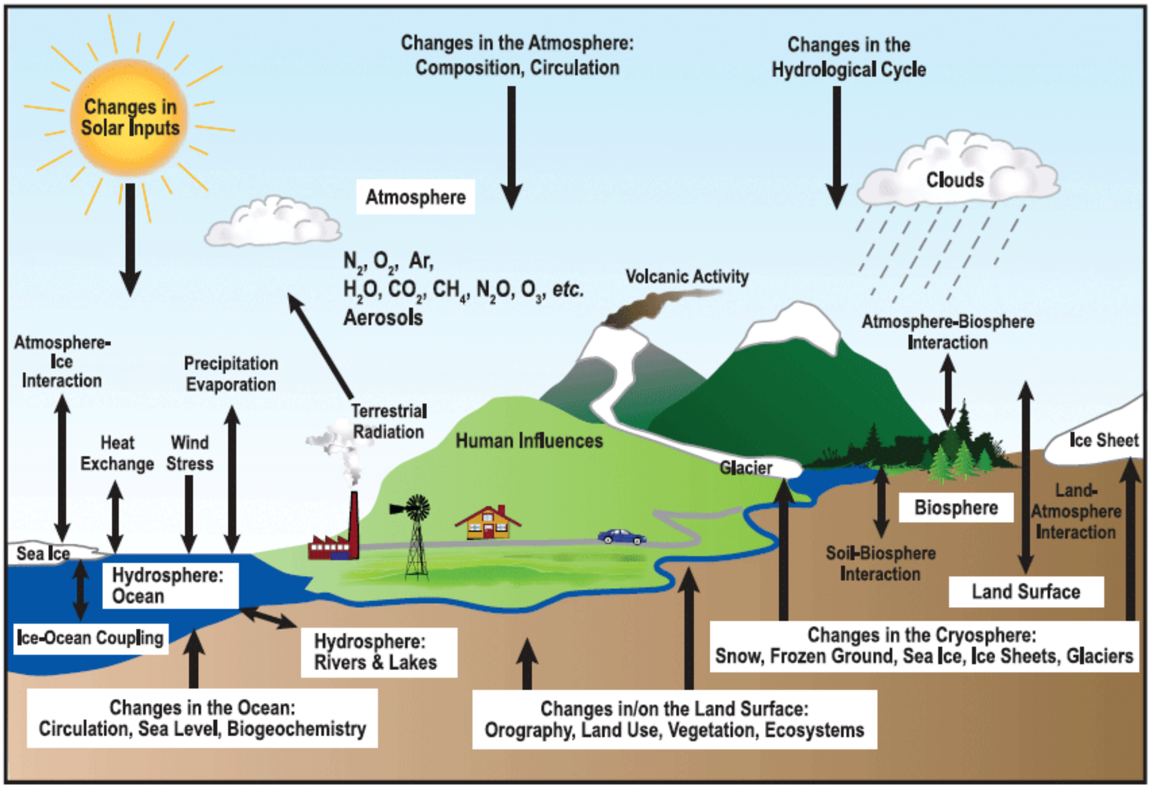
BOX 3.2 Forcing a Climate Model

The term "forcing" as used in Chapter 3 refers to a process for subjecting a climate model to a specified influence, often with the intention to probe cause-effect relationships. The imposed conditions could be "fixed" in time, such as a might be used to represent a sudden emission of aerosols by volcanic activity. It may be "time evolving" such as by specifying the history of sea surface temperature variations in an atmospheric model. The purpose of forcing a model is to study the Earth system response, and the degrees of freedom sensitivity of that response to both the model and the forcing employed. The schematic of the climate system helps to better understand the forcings used in various models of Chapter 3.

For atmospheric model simulations used in this SAP, the forcing consists of specified monthly evolving global sea surface temperatures during 1951 to 2006. By so restricting the lower boundary condition of the simulations, the response of unconstrained features of the climate system can be probed. In this SAP, the atmosphere and land surface are free to respond. Included in the former are the atmospheric hydrologic cycle involving clouds, precipitation, water vapor, temperature, and free atmospheric circulation. Included in the latter is soil moisture and snow cover, and changes in these can further feedback upon the atmosphere. Sea ice has been specified to climatological conditions in the simulations of this report, as has the chemical composition of the atmosphere including greenhouse gases, aerosols, and solar output.

For coupled ocean-atmosphere model simulations used in this SAP, the forcing consists of specified variations in atmospheric chemical composition (*e.g,*, carbon dioxide, methane, nitrous oxide), solar radiation, volcanic and anthropogenic aerosols. These are estimated from observations during 1951 to 2000, and then based upon a emissions scenario for 2001 to 2006. The atmosphere, land surface, ocean, and sea ice are free to respond to these specified conditions. The atmospheric response to those external forcings could result from the altered radiative forcing directly, though interactions and feedbacks involving the responses of the lower boundary conditions (*e.g.*, oceans and cryosphere) are often of leading importance. For instance, much of the high-latitude amplification of surface air temperature warming due to greenhouse gas emissions is believed to result from such sea ice and snow cover feedback processes. Neither the coupled ocean-atmospheric models nor the atmospheric models used in this SAP include changes in land surface, vegetation, or ecosystems. Nor does the oceanic response in the coupled models include changes in biogeochemistry.

Multiple realizations of the climate models subjected to the same forcings are required in order to effectively separate the climate model's response from low-frequency climate variability. Ensemble methods are therefore used in Chapter 3. In the case of the atmospheric models, 33 total simulations (derived from two different models) forced as discussed above are studied. In the case of the coupled ocean-atmosphere models, 41 total simulations (derived from 19 different models) forced as discussed above are studied.



Box Figure 3.2-1 Schematic view of the components of the climate system, their processes and interactions (from “Climate Change 2007: The Physical Science Basis”; IPCC, 2007a).

******** END BOX 3.2 *************

iii) Attribution to external forcing

Explaining the origins for the surface boundary conditions themselves is another stage in attribution. El Niño, for example, is a known internal variation of the coupled ocean-atmosphere. On the other hand, a warming trend of ocean SST, as seen in recent decades over the tropical warm pool of the Indian and west Pacific Oceans, is recognized to result in part from changes in greenhouse gas forcing (Santer *et al.*, 2006; Knutson *et al.*, 2006). Figure 3.1 highlights the very different character of time variations in SSTs over the east and west tropical Pacific that captures different processes occurring in those regions. The climate effects of recent warm-pool warming on North American climate might thus be judged to be of external origins to the ocean-atmosphere system, tied in part to changes in the atmosphere's chemical composition.

The third link in the attribution chain thus involves attribution of observed climate conditions to external forcing. The external forcing could be natural, for instance originating from volcanic aerosol effects or solar fluctuations. Or, the external forcing could be anthropogenic resulting from human activities. As discussed extensively in the IPCC reports, the attribution of climate conditions to external driving can be done directly by specifying the natural and anthropogenic forcings within coupled ocean-atmosphere-land models. An indirect approach can also be employed to attribute a climate conditions to external forcing. An example would be probing the response of an atmospheric model to SST conditions believed to have been externally forced (Hoerling *et al.*, 2004). Note, however, that if an indirect chain is used, it can only be *qualitatively* determined that external forcing contributed to the event - an accurate *quantification* of the magnitude of the impact by external forcing can only be determined in a direct approach.

The tool used for attribution of external forcing, either to test the signal due to anthropogenic greenhouse gas, aerosol changes or land use changes, or natural external forcing due to volcanic and solar forcing, involves coupled ocean-atmosphere-land models forced by observed external forcing variations. As illustrated in Figure 3.1, this methodology has been widely used in the IPCC reports to date. Several studies have used reanalysis data to first detect change in atmospheric circulation, and then test with models whether such change resulted from human influences (Chapter 2 also discusses the use of reanalysis data in establishing the suitability of climate models used for attribution). For instance, a trend in wintertime sea level pressure has been observed and confirmed in reanalysis data that resembles the positive polarity of the NAO, and greenhouse gas and sulphate aerosol changes due to human activities have been implicated as a contributing factor (Gillett *et al.*, 2003; Figure 3.7). Reanalysis data have been used to detect an increase in the height of the tropopause - a boundary separating the troposphere and stratosphere, and modeling results have established human induced changes in stratospheric ozone and greenhouse gases as the primary cause (Santer *et al.*, 2003).

3.1.2.2 Fingerprinting

Many studies use climate models to predict the expected pattern of response to a forcing, referred to as “fingerprints” in the classic climate change literature, or more generally referred to as the “signal” (Mitchell *et al.*, 2001; IDAG, 2005; Hegerl *et al.*, 2007). The spatial and temporal scales used to analyse climate conditions are typically chosen so as to focus on the spatial-temporal scale of the signal itself, filtering out as much structure that is believed to be unrelated to forcing. For example, it is expected that greenhouse gas forcing would cause a large-scale pattern of warming that evolves slowly over time, and thus scientists often smooth data to remove small-scale variations in both time and space. On the other hand, it is expected that El Niño-related SST forcing yields a regionally focused pattern over the Pacific North American sector, having several nodal positions separating regions of opposite signed signal, and thus large-spatial scale smoothing is inappropriate. Furthermore, to ensure that a robust signal has been derived from climate models, individual realizations of an ensemble - in which each member has been identically forced - are averaged. Ensemble methods thus are essential in separating the model's forced signal from its internal variability so as to minimize the confounding of signal and noise.

The consistency between an observed climate condition and the estimated response to a hypothesised key forcing is determined by (1) estimating the amplitude of the expected fingerprint empirically from observations, (2) assessing whether this estimate is statistically consistent with the expected amplitude derived from forced model experiments, and then (3) inquiring whether the fingerprint related to the key forcing is distinguishable from that due to other forcings. The capability to do so also depends on the amplitude of the expected fingerprint relative to the noise resulting from unforced climatic fluctuations.

In order to separate the contribution by different forcings and investigate if other combinations of forcing can also explain an observed event, the simultaneous effect of multiple forcings are also examined, typically using a multiple regression of observations onto several fingerprints representing climate responses to each forcing that, ideally, are clearly distinct from each other (Hasselmann, 1979; 1997; Allen and Tett, 1999; IDAG, 2005; Hegerl *et al.*, 2007). Examples of this are the known unique sign and global patterns of temperature response to increased anthropogenic sulphate aerosols versus increased carbon dioxide. A further example is the known different spatial patterns of atmospheric circulation response over the North American region to SST forcing from the Indian Ocean compared to the tropical east Pacific ocean (Simmons *et al.*, 1983; Barsugli and Sardeshmukh, 2002). If the responses to these key forcings can be distinguished, and if rescaled combinations of the responses to other forcings do not sufficiently explain the observed change, then the evidence for a causal connection is substantially increased. Thus, the attribution of recent large-scale warming to greenhouse gas forcing becomes more reliable if the influences of other natural external forcings, such as solar variability, are explicitly accounted for in the analysis.

The confidence in attribution will thus be subject to the uncertainty in the fingerprints both estimated empirically from observations and numerically from forced model simulations. The effects of forcing uncertainties, which can be considerable for some forcing agents such as solar and aerosol, also remain difficult to evaluate despite recent advances in research.

Satellite and in situ observations during the reanalysis period yield reliable estimates of SST conditions over the world oceans, thus increasing the reliability of attribution based on SST forced atmospheric models. Estimates of other land surface conditions including soil moisture and snow cover are less reliable. Attribution results based on several models or several forcing histories also provide information on the effects of model and forcing uncertainty. Likewise, empirical estimates of fingerprints derived from various observational datasets provide information of uncertainty.

Finally, attribution requires knowledge of the internal climate variability on the time scales considered - the so-called “noise” within the system against which the signal is to be detected and explained. The residual variability that remains in instrumental observations of the Earth System after the estimated effects of external forcing (greenhouse gases and aerosols) have been removed is sometimes used to estimate internal variability of the coupled system. However, these observational estimates are uncertain because the instrumental records are too short to give a well-constrained estimate of internal variability, and because of uncertainties in the forcings and the corresponding estimates of responses. Thus, internal climate variability is usually estimated from long control simulations from climate models. Subsequently, an assessment is usually made of the consistency between the residual variability referred to above and the model-based estimates of internal variability; and analyses that yield implausibly large residuals are not considered credible. Confidence is further increased by comparisons between variability in observations and climate model data, by the ability of models to simulate modes of climate variability, and by comparisons between proxy reconstructions and climate simulations of the last millennium.

The following sections of this Chapter summarize current understanding on the causes of detected changes in North American climate. Sections 2 through 5 will illustrate uses of reanalysis data in combination with surface temperature and precipitation measurements to examine the nature of North American climate variations, and compare with forced model experiments that test attributable cause. In addition, the section also assesses the state of understanding of causes for other variations of significance in North America’s recent climate history, focusing especially on major North American droughts. In the mid-1930s Congress requested that the Weather Bureau explain the causes for the 1930s Dust Bowl drought, with a key concern being to understand whether this event was more likely a multi-year occurrence or a harbinger of longer-term change. As 70 years earlier, fundamental challenges in attribution science today are to distinguish quasi-cyclical variations from long-term trends, and natural from anthropogenic origins.

3.2 WHAT IS THE PRESENT UNDERSTANDING OF THE CAUSES FOR THE NORTH AMERICAN CLIMATE TRENDS IN ANNUAL TEMPERATURE AND PRECIPITATION DURING THE REANALYSIS PERIOD?

3.2.1 Summary of IPCC Fourth Assessment Report

Among the major findings of the IPCC Fourth Assessment (IPCC, 2007b) is that "it is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica". This conclusion was based on recent fingerprint-based studies on the attribution of annual surface temperature involving space-time patterns of temperature variations and trends. Model studies using only natural external forcings were shown to be unable to explain the warming over North America in recent decades, and only experiments including the effects of anthropogenic forcings reproduced the recent upward trend. The IPCC report also stated that for precipitation there was low confidence in detecting and attributing a change, especially at the regional scale.

This assessment focuses in greater detail on North American temperature and precipitation variability during the period 1951 to 2006.

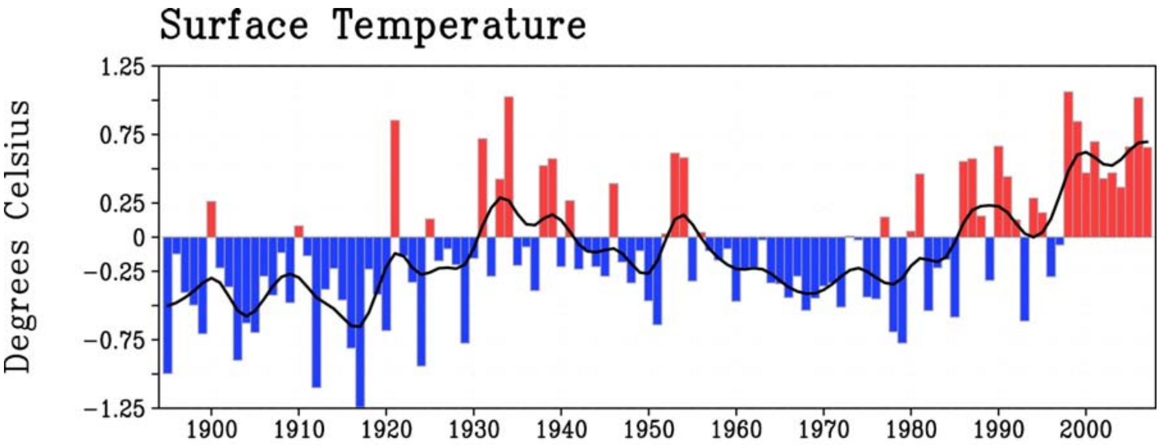
BOX 3.3 Choosing the Assessment Period

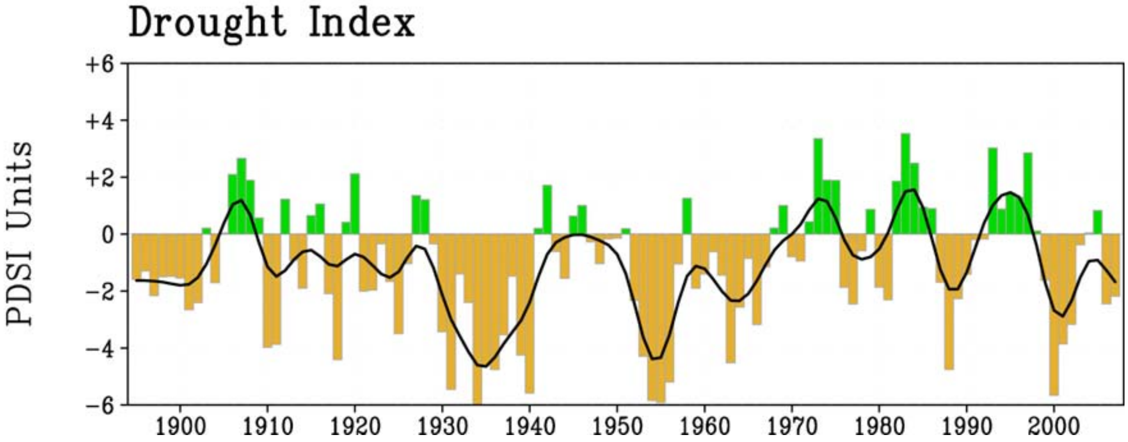
This SAP report was asked to examine the strengths and limitations of current reanalysis products, and to assess capabilities for attributing the causes for climate variations and trends during the reanalysis period. This assessment's scope is thus bounded by the reanalysis record (1948 to present). An important further consideration is the availability of sufficient, quality controlled surface observations to define key climate variations accurately. For precipitation, a high quality global gridded analysis is available beginning in 1951, thereby further focusing the attribution to 1951 to 2006.

It is reasonable to ask whether such a 56-year assessment period adequately samples the principal features of climate variability. Does it, for example, capture the major climate events that may be of particular concern to decision makers, such as droughts? Is it a sufficiently long period to permit the distinction between fluctuations in climate conditions that are transient, or are cyclical, from trends that are related to a changing climate? How well do scientists understand the climate conditions prior to 1951, and what insight does analysis of those provide toward explaining post-1950 conditions? These are all important questions to bear in mind when reading this Report, and especially if one wishes to generalize conclusions about the nature of and causes for climate conditions during 1951 to 2006 to earlier or future periods.

As a case in point, the U.S. surface temperature record since 1895 is remarkable for its multi-decadal fluctuations (top panel). A simple linear trend fails to describe all features of U.S. climate variations, and furthermore, a trend analysis for any subset of this 112-year period may be problematic since it may capture merely a segment of a transient oscillation. The decade of the 1930s and 40s was a particularly warm period, one only recently eclipsed. The U.S. has thus undergone two major swings between cold epochs (beginning in the 1890s and 1960s) and warm epochs (1930s and 2000s). It is reasonable to wonder whether the current warmth will also revert to colder conditions in coming decades akin to events following the 1930s peak, and attribution science is therefore important for determine whether the same factors are responsible for both warmings or not. Some studies reveal that the earlier warming may have resulted from a combination of anthropogenic forcing and an unusually large natural multi-decadal fluctuation of climate (Delworth and Knutson, 2000). Other work indicates a contribution to the early 20th century warming by natural forcing of climate, such as changes in solar radiation or volcanism (*e.g.*, Tett *et al.*, 2002; Hegerl *et al.*, 2006). The 1930s warming was part of a warming focused mainly in the northern high latitudes, a pattern reminiscent of an increase in poleward ocean heat transport (Rind and Chandler; 1991), which can itself be looked upon as due to "natural variability". In contrast, the recent warming is part of a global increase in temperatures, and the IPCC Fourth Assessment Report chapter 9 states that it is likely that a significant part of warming over the past 50 years over North America may be anthropogenically related, thus contrasting causes of the warming that occurred in this period from that in 1930s. The physical processes related to this recent warming are further examined in Chapter 3.

The year 1934 continues to stand out as one the warmest years in the U.S. 112-year record, while averaged over the entire globe, 1934 is considerably cooler than the recent decade. The U.S. warmth of the 1930s coincided with the Dust Bowl (lower panel), and drought conditions likely played a major role in driving up land surface temperatures. Prior studies suggest that the low precipitation during the Dust Bowl was related in part to sea surface temperature conditions over the tropical oceans (Schubert *et al.*, 2004a,b; Seager *et al.*, 2005). Our understanding of severe U.S. droughts that have occurred during the reanalysis period as described in Chapter 3 builds upon such studies of the Dust Bowl.





Box Figure 3.3-1 Time series of U.S. area averaged and annually averaged surface air temperature (top) and the Palmer Drought Severity Index (bottom) for the period 1895 to 2006. The smooth curve is a result of applying a 9-point Gaussian filter to the annual values in order to highlight lower frequency variations. Data source is the contiguous U.S. climate division data of NOAA's National Climatic Data Center.

********** END BOX 3.3 ***************

The origins for the North American fluctuations is assessed by examining the impacts on North America from time evolving sea surface conditions (including ENSO and decadal ocean variations), in addition to time evolving anthropogenic effects. The use of reanalysis data to aid in the attribution of surface climate conditions is illustrated.

3.2.2 North American Annual Mean Temperature

3.2.2.1 Description of the observed variability

Seven of the warmest ten years since 1951 have occurred in the last decade (1997 to 2006).

The manner in which North American annual temperatures have risen since 1951, however, has been neither smooth nor consistent; its trajectory has been punctuated by occasional peaks and valleys (Figure 3.3, top). The coldest year since 1951 occurred in 1972, and below average annual temperatures occurred as recently as 1996. Explanations for such substantial variability is no less important than explanations for the warming trend.

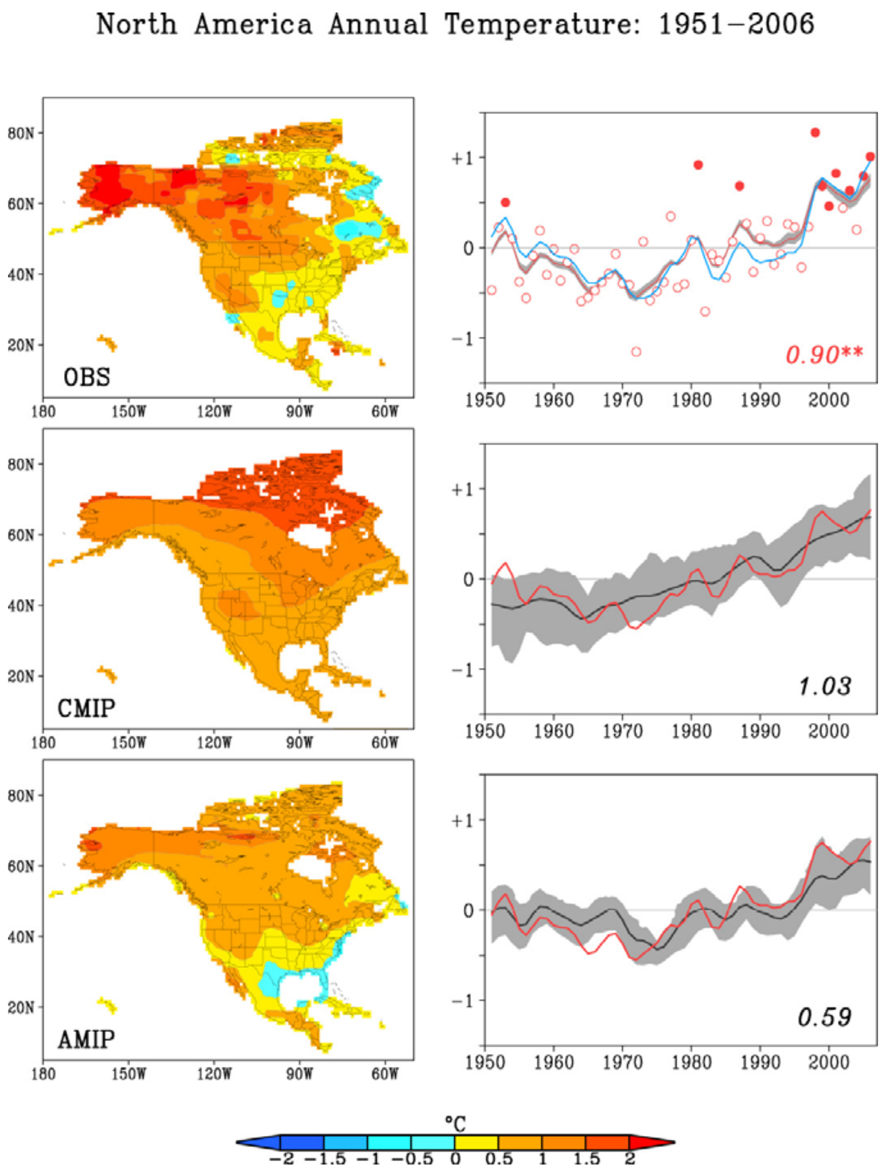


Figure 3.3 The 1951 to 2006 trend in annually averaged North American surface temperature from observations (top), CMIP simulations (middle), AMIP simulations (bottom). Maps (left side) show the linear trend in annual temperatures for 1951 to 2006 (units, °C/56 years). Time series (right side) show the annual values from 1951 to 2006 of surface temperatures averaged over the whole of North America. Curves are smoothed annual values using a 5-point Gaussian filter, based on the average of four gridded surface observational analyses, and the ensemble mean of climate simulations. Unsmoothed annual observed temperatures shown by red circles, with filled circles denoting the ten warmest years since 1951. Plotted values are the total 56-year change (°C), with the double asterisks denoting very high confidence that an observed change was detected. For observations, the gray band denotes the range among four surface temperature analyses. The blue curve is the NCEP/NCAR reanalysis surface temperature time series. For simulations, the gray band contains the 5-95% occurrence of individual model simulations.

Virtually all of the warming averaged over North America since 1951 has occurred after 1970. It is noteworthy that North American temperatures cooled during the period 1951 through the early 1970s. In the 1970s, the public and policy makers were keenly interested to know the reason for this cooling, with concerns about food production and societal disruptions. They turned to the meteorological community for expert assessment. Unfortunately, climate science was at its infancy in the 1970s and attribution was considerably more art than science. The essential tools for performing rigorous attribution such as global climate models were not yet available, nor was much known then about the range of historical climate variations such as has been subsequently revealed by paleoclimate studies. A consistent climate analysis of the historical instrumental record that included descriptions of the free atmosphere was also unavailable.

Barring an explanation of the cause for the cooling, and with no comprehensive climate models available, some scientists responded to the public inquiries on what would happen next by merely extrapolating recent trends thereby portraying enhanced risk for a cooling world (Kukla and Mathews, 1972; Newsweek, 1975). Others suggested, in the mid-1970s that we might be at the brink of a pronounced global warming, arguing that internal variations of the climate were then masking an anthropogenic signal (Broecker, 1975). The 1975 National Academy of Sciences report on (NRC, 1975) understanding climate change emphasized the fragmentary state of knowledge of the mechanisms causing climate variations and change, and posed the question whether we would be able to recognize the first phases of a truly significant climate change when it does occur (NRC, 1975). Perhaps the single most important attribution challenge today regarding the time series of Figure 3.3 is whether the reversal of the cooling trend after 1975 represents such a change, and one for which a causal explanation can be offered.

There is very high confidence in the detection that the observed temperature trend reversed after the early 1970s. The shaded area in Figure 3.3 (top) illustrates the spread among four different analyses of surface measurements (see Table 3.2 for descriptions of these data), and the analysis uncertainty as revealed by their range is small compared to the amplitude of the trend and principal variations. Also shown is the surface temperature time series derived from the reanalysis. Despite the fact that the assimilating model used in producing the NCEP/NCAR reanalysis does not ingest surface temperature observations (Kalnay *et al.*, 1996), the agreement with the in situ observations is strong. This indicates that the surface temperature averaged over the large domain of North America is constrained by and is consistent with climate conditions in the free atmosphere. Both for the emergent warming trend in the 1970s, and for the variations about it, this excellent agreement among time series based on different observational data sets and the reanalysis increases confidence that they are not artifacts of analysis procedure.

The total 1951 to 2006 change in observed North American annual surface temperatures is +0.90°C +/- 0.1°C, with the uncertainty estimated from the range between trends derived from four different observational analyses. Has a *significant* North American warming been detected? Answers to this question require knowledge of the plausible range in 56-year trends that can occur naturally in the absence of any time varying anthropogenic forcing. The brevity of the observational record does not permit such an assessment, but an analysis of such variations in coupled model simulations that exclude variations in anthropogenic forcing provides an indirect estimate. To estimate the confidence that a change in North American temperatures has been detected, a non-parametric test has been applied that estimates the range of 56-year trends attributable to natural variability alone (see Appendix 3.A for methodological details). A diagnosis of 56-year trends from the suite of "naturally forced" CMIP runs is performed, from which a sample of 76 such trends were generated for annual North American averaged surface temperatures. Of these 76 "trends estimates" consistent with natural variability, no single estimate was found to generate a 56-year trend as large as observed.

It is thus *very likely* that a change in North American annual mean surface temperature has been detected. That assessment weighs the realization that the climate models have biases that can affect statistics of their simulated internal climate variability.

3.2.2.1 Attribution of the observed variations

3.2.2.1.1 External Forcing

The Fourth Assessment Report of the IPCC provided strong attribution evidence for a significant anthropogenic warming of North American surface temperatures. Figure 3.4 is drawn from that report, and compares continental-averaged surface temperature changes observed with those simulated using the CMIP coupled models having natural and anthropogenic forcing. It is clear that only experiments using time varying observed

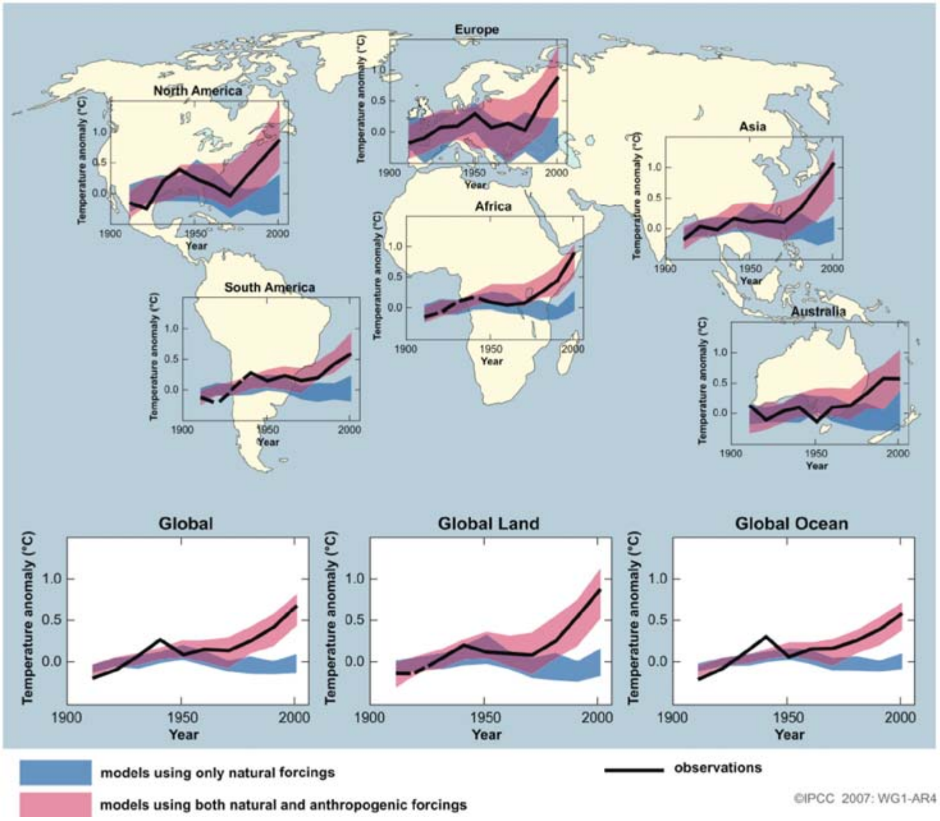


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Figure 3.4 Temperature changes relative to the corresponding average for 1901 to 1950 (°C) from decade to decade from 1906 to 2005 over the Earth's continents, as well as the entire globe, global land area and the global ocean (lower graphs). The black line indicates observed temperature change, while the colored bands show the combined range covered by 90% of recent model simulations. Red indicates simulations that include natural and human factors, while blue indicates simulations that include only natural factors. Dashed black lines indicate decades and continental regions for which there are substantially fewer observations. Detailed descriptions of this figure and the methodology used in its production are given in Hegerl (2007).

anthropogenic forcing explain the warming in recent decades. Numerous detection and attribution studies, as reviewed by Hegerl *et al.* (2007), have shown that the observed warming of North American surface temperature since 1950 cannot be explained by natural climate variations alone and is consistent with the response to anthropogenic climate forcing, particularly increases in greenhouse gases (Karoly *et al.*, 2003; Stott, 2003; Zwiers and Zhang, 2003; Knutson *et al.*, 2006; Zhang *et al.*, 2006). The suitability of these coupled climate models for attribution is indicated by the fact that they are able to simulate variability on decadal time scales and longer that is consistent with reanalysis data of the free atmosphere and surface observations over North America (Hegerl *et al.*, 2007, Figure 9.8).

A more detailed examination of the anthropogenic influence on North America is provided in Figure 3.3 (middle) that shows the spatial map of the 1951 to 2006 simulated surface temperature trend, in addition to the time series. There are several key agreements between the CMIP simulations and observations that support the argument for an anthropogenic effect. First, both indicate the bulk of warming to have occurred in the past 30 years. The emergence of North American warming after 1970 is thus *likely* the result of the region's response to anthropogenic forcing. Second, the total 1951 to 2006 change in observed North American annual surface temperatures of +0.90°C compares well to the simulated ensemble averaged warming of +1.03°C. Whereas the observed 56-year trend was shown in the previous subsection to be inconsistent with the population of trends drawn from a state of natural climate variability, the observed warming is found to be consistent with the population of trends drawn from a state that includes observed changes in the anthropogenic forcing during 1951 to 2006.

Further, the observed low frequency variations of annual temperature fall within the 5-95% uncertainty range of the individual model simulations. All CMIP runs that include anthropogenic forcing produce a North American warming during 1951 to 2006. For some simulations, the trend is less than that observed and for some it is greater than that observed. This range results from both the uncertainty in anthropogenic signals (owing to different sensitivities of the 19 models) and the effects of model internal variability (owing to sensitivity of individual runs of the same models to natural coupled-ocean atmosphere fluctuations).

Each of the 41 anthropogenically forced simulations produce a 56-year North American warming (1951 to 2006) that is greater than half of the observed warming. Our assessment of the origin for the observed North American surface temperature trend is that more than half of the warming during 1951 to 2006 is *likely* the result of anthropogenic influences. It is *exceptionally unlikely* that the observed warming has resulted from natural variability alone because there is a clear separation between the ensembles of climate model simulations that include only natural forcings and those that contain both anthropogenic and natural forcings (Hegerl *et al.*, 2007). These confidence statements reflect the uncertainty of the role played by model biases in their sensitivity to external forcing, and also the unknown impact of biases on the range of their unforced natural variability.

BOX 3.4 Use of Expert Assessment

The use of expert assessment is a necessary element in attribution as a means to treat the complexities that generate uncertainties. Expert assessment is used to define levels of confidence, and the terms used in this Report (see Preface) follow those of the IPCC Fourth Assessment Report. The attribution statements used in Chapter 3 of this SAP also employ probabilistic language (for example, “virtually certain”) to indicate a likelihood of occurrence.

To appreciate the need for expert assessment, it is useful to highlight the sources of uncertainty that arise in seeking the cause for climate conditions. The scientific process of attribution involves various tools to probe cause-effect relationships such as historical observations, climate system models, and mechanistic theoretical models. Despite ongoing improvements in reanalysis and models, these and other tools have inherent biases rendering explanations of the cause for a climate condition uncertain. Uncertainty can arise in determining a forced signal (*i.e.*, fingerprint identification). For instance, the aerosol-induced climate signal involves direct radiative effects that require on accurate knowledge of the amount and distribution of aerosols in the atmosphere. These are not well observed quantities, leading to so-called “value uncertainties” (IPCC, 2007a) because the forcing itself is poorly known. The aerosol-induced signal also involves an indirect radiative forcing, the latter depending on cloud properties and water droplet distributions. These cloud radiative interactions are poorly represented in current generation climate models (Kiehl, 1999), contributing to so-called "structural uncertainties" IPCC, 2007a). Even if the forcing is known precisely and the model includes the relevant processes and relationships, the induced signal may be difficult to distinguish from other patterns of climate variability thereby confounding the attribution.

The scientific peer-reviewed literature provides a valuable guide to the author team of Chapter 3 for determining attribution confidence. In addition, new analyses in this SAP are also examined in order to provide additional information. These employ methods and techniques that have been extensively tested and used in the scientific literature. In most cases, new analyses involve observational data and model simulations that have merely updated to include recent years through 2006.

********** END BOX 3.4 ************

Regarding the yearly fluctuations in observed North American temperature, it is evident in Figure 3.3 that these are of greater amplitude than those occurring in the ensemble average of externally forced runs. This is consistent with the fact that the former commingles the effects of internal and external influences while the latter estimates only the time evolving impact of external forcings. Nonetheless, several of these observed fluctuations align well with those in the CMIP data. In particular, the model warming trend is at times punctuated by short periods of cooling, and these episodes coincide with major tropical volcanic eruptions (*e.g.*, Aguang in 1963; Mt. Pinatubo in 1991). Such natural externally forced cooling episodes correspond well with periods of observed cooling, as will be discussed further in Section 3.4.

3.2.2.1.1 Sea Surface Temperature Forcing

The oceans play a major role in climate, not only for determining its mean conditions and seasonal cycle, but also for determining its anomalous conditions including interannual to decadal fluctuations. Section 3.1 discussed modes of anomalous SST variations that impact North America, in particular that associated with ENSO. Figure 3.5 illustrates the temporal variations of SSTs over the global oceans and over various ocean basins during

1951 to 2006. Three characteristic features of the observed SST fluctuations are noteworthy. First, SSTs in the east tropical Pacific (top panel) vary strongly from year to year, as warm events alternate with cold events indicative of the ENSO cycle. Extratropical North Pacific and North Atlantic SSTs have strong year-to-year persistence, with decadal periods of cold conditions followed by decadal periods of warm conditions. Finally, the warm pool of the Indian Ocean-west tropical Pacific, the tropically averaged SSTs, and globally averaged SSTs are dominated by a warming trend. These resemble in many ways the time series of North American surface temperatures including a fairly rapid emergence of warmth after the 1970s.

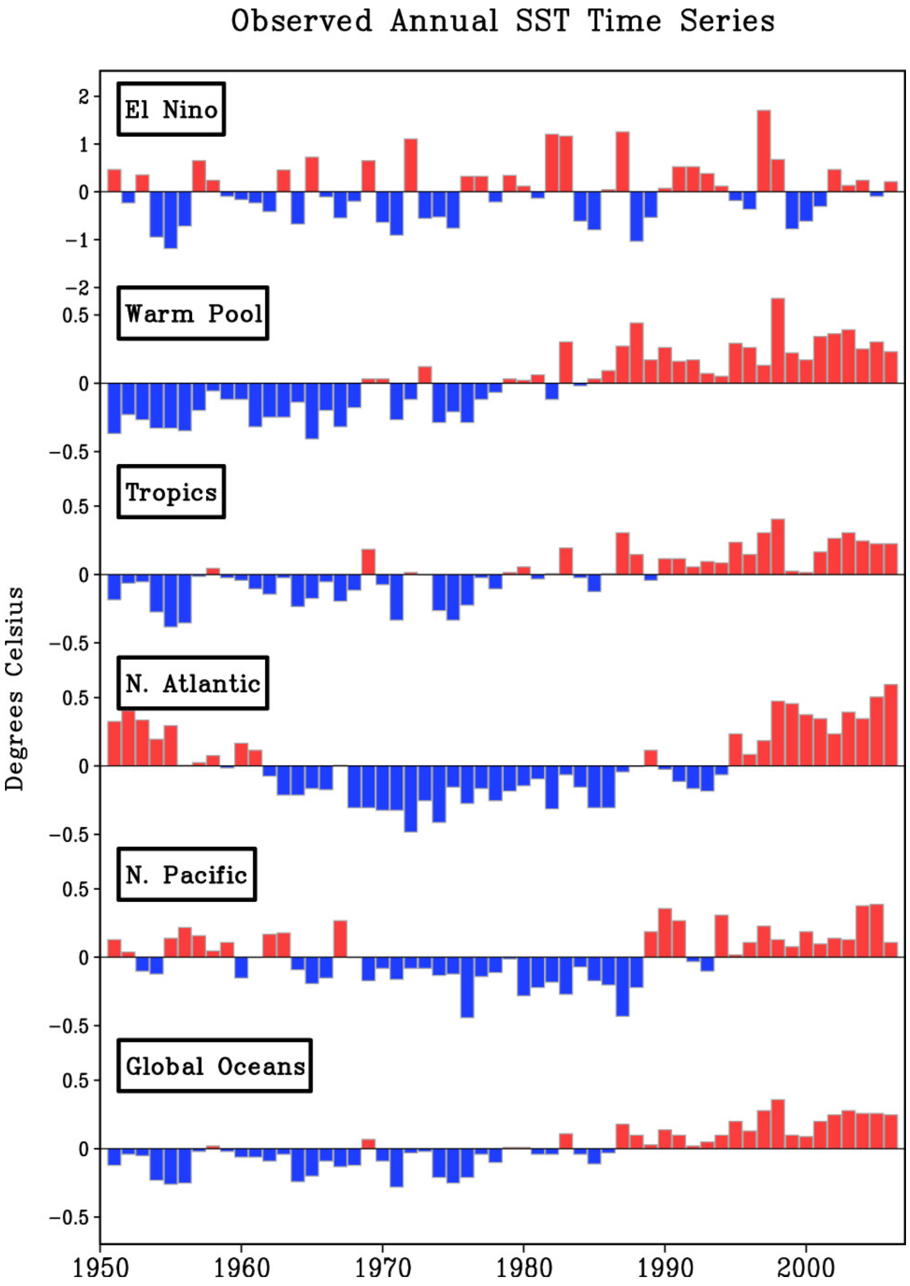

Figure 3.5 Observed annual mean SST time series for 1951 to 2006. The oceanic regions used to compute the indices are 5°N-5°S, 90°W-150°W for El Niño, 10°S-10°N, 60°E-150°E for the warm pool, 30°S-30°N for the tropics, 30°N-60°N for the North Atlantic, 30°N-60°N for the North Pacific, and 40°S-60°N for the global oceans. Data set is the HadiSST monthly gridded fields, and anomalies are calculated relative to a 1951 to 2006 reference.

A common tool for determining the SST effects on climate is atmospheric general circulation models (AGCM) forced with the specified time evolution of the observed

SSTs, in addition to empirical methodologies (see Figure 3.2 for the El Niño impact inferred from reanalysis data, and Box 3.1 for an assessment of model simulated ENSO teleconnections). Such numerical modeling approaches are generally referred to as AMIP simulations (Gates, 1992), and here we adapt that term to refer to model runs spanning the period 1951 to 2006.

Much of the known effect of SSTs has focused on the boreal winter season, a time when El Niño and its North American impacts are at their peak. However, the influence of SSTs on *annual mean* variability over North America is not yet documented in the peer-reviewed literature. Therefore, we present here an expert assessment based on the analysis of two AGCMs (Table 3.1). It is important to note that the AMIP simulations used in this analysis do not include the observed evolution of external forcings, *e.g.*, solar, volcanic aerosols, or anthropogenic greenhouse gases. The specified SSTs may, however, reflect the footprints of such external influences. See Section 3.4 and Figure 3.18 for a discussion of the same SST time series constructed from the CMIP simulations.

North American annual temperature trends, and their temporal evolution, are well replicated in the AMIP simulations (Figure 3.3, bottom). There are several key agreements between the AMIP simulations and observations that support the argument for an SST effect. First, the bulk of the AMIP simulated warming occurs after 1970 as in observations. The time evolution of simulated annual North American surface temperature fluctuations is very realistic, with a temporal correlation of 0.79 between the raw unsmoothed observed and simulated annual values. While slightly greater than the observed versus CMIP agreement of 0.68, much of the positive year-over-year correlation owes to the warming trend. Second, the pattern correlation of 0.87 with the observed trend map highlights the remarkable spatial agreement, and exceeds the 0.79 spatial correlation for the CMIP simulated trend. Several other notable features of the AMIP simulations include the greater warming over western North America and slight cooling over eastern and southern United States regions. The total 1951 to 2006 change in observed North American annual surface temperatures of +0.90°C compares well to the AMIP simulated warming of +0.59°C.

There exists a strong congruence between the AMIP and CMIP simulated North American surface temperature trend patterns and their time evolutions during 1951 to 2006. This comparison of the CMIP and AMIP simulations indicates that a substantial fraction of the area-average anthropogenic warming over North America has *likely* occurred as a consequence of sea surface temperature forcing. The physical processes by which the oceans have led to North American warming is not, however, currently known.

An important attribution challenge is determining which aspects of regional SST variability during 1951 to 2006 have been important in rendering the signals in Figure 3.3. Idealized studies linking regional SST anomalies to atmospheric variability have been conducted (Hoerling *et al.*, 2001; Robertson *et al.*, 2003; Barsugli *et al.*, 2002; Kushnir *et al.*, 2002); however, a comprehensive suite of model simulations to address variability in North American surface temperatures during 1951 to 2006 has yet to be undertaken. Whereas the North American sensitivity to SST forcing from the El Niño region is well understood, less well known is the effect of the progressive tropical-wide SST warming, a condition that has been the major driver of globally averaged SST behavior during the last half century (Figure 3.5). A further question is the effect that recent decadal warming of the North Pacific and North Atlantic Oceans have had on North American climate, either in explaining the spatial inhomogeneity in North American temperature trends, or as a factor in the accelerated pace of North American warming post-1970. Although the desired simulation suite have yet to be conducted, some attribution evidence for regional SST effects can be gleaned empirically from the reanalysis data itself which are capable of describing changes in tropospheric circulation patterns, elements of which are known to have regional SST sources. This will be the subject of further discussion in Section 3.3, where post-1950 observed changes in PNA and NAO circulation patterns are described and their role in North American climate trends is assessed.

3.2.2.1.2 Analysis of Annual Mean Rainfall Variability Over North America

In contrast to temperature, North American precipitation exhibits considerably greater spatial and temporal variability. The annual cycle of precipitation is itself vastly heterogeneous over the continent, with winter maxima along western North America, summertime maxima over Mexico and Central America, and comparatively little amplitude to the seasonal cycle over eastern North America. It is therefore not surprising that the 1951 to 2006 trend in annual precipitation is dominated by regional scale features (Figure 3.6, top). Several of these are discussed further in Section 3.3.

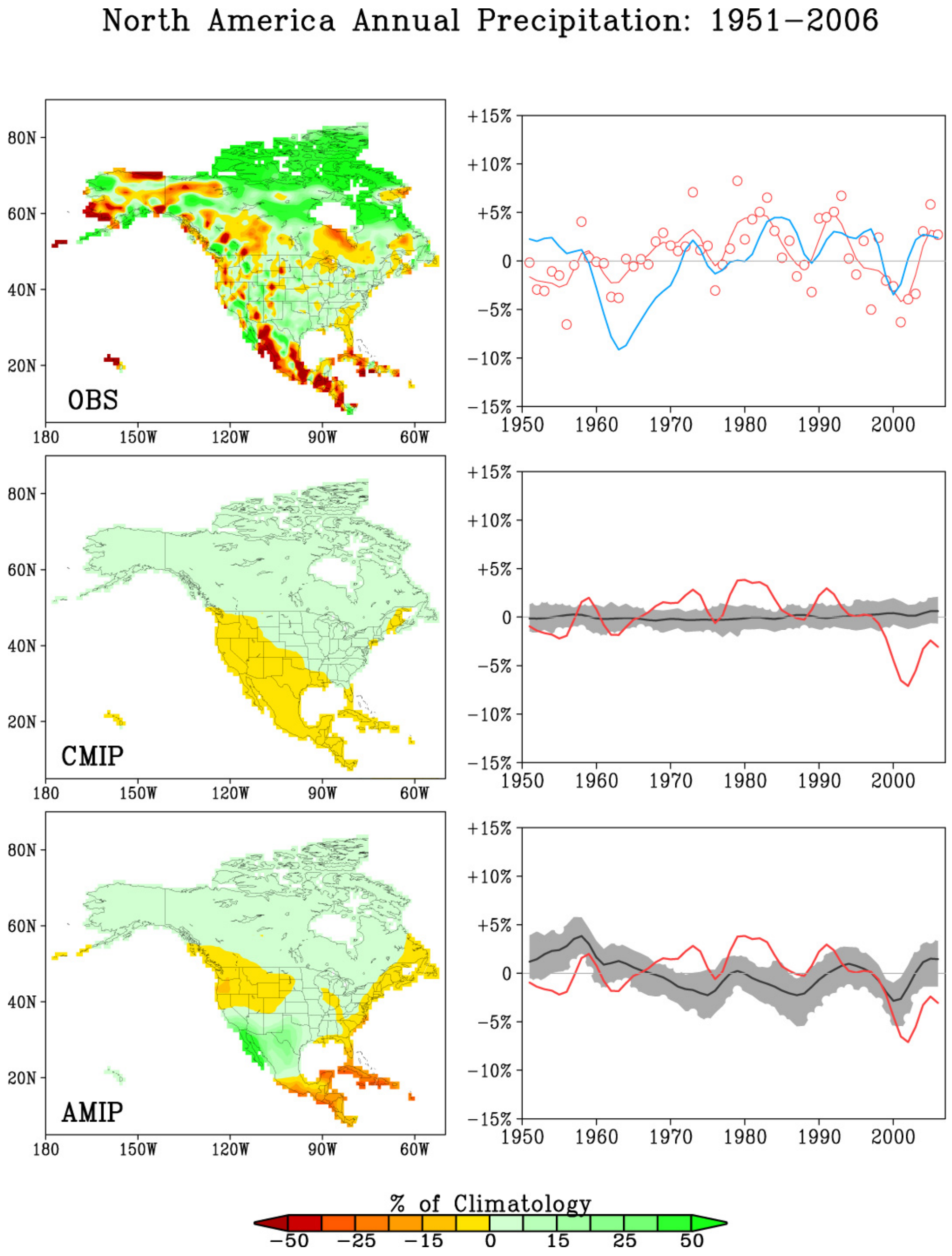

Figure 3.6 The 1951 to 2006 trend in annually averaged North American precipitation from observations (top), CMIP simulations (middle), AMIP simulations (bottom). Maps (left side) show the linear trend in annual precipitations for 1951 to 2006 (units, total 56-year change as % of climatology). Time series (right side) show the annual values from 1951to 2006. Curves are smoothed annual values using a 5-point Gaussian filter, based on the GPCC observational analysis, and the ensemble mean of climate simulations. Unsmoothed annual observed precipitation shown by red circles. The blue curve is the NCEP/NCAR reanalysis precipitation time series. For simulations, the gray band contains the 5-95% occurrence of individual model simulations.

For area-averaged North America as a whole, there is no coherent trend in observed precipitation since 1951. The time series of annual values has varied within 10% of the climatological average, with the most notable feature being the cluster of dry years from the late 1990s to the early 2000s. However, even these annual variations for North American averaged precipitation as a whole are of uncertain physical significance. This is because of the regional focus of precipitation fluctuations, and the considerable cancellation between anomalies of opposite sign when averaging across the continent as is done in Figure 3.6.

Neither externally forced nor SST forced simulations show a significant change in North American-wide precipitation since 1951. In addition, the area averaged annual fluctuations in the simulations are generally within a few percent of climatology (Figure 3.6, middle and bottom panels). The comparison of the observed and CMIP simulated North America precipitation indicates that the anthropogenic signal is small relative to the observed variability on annual and decadal timescales. As a note of caution regarding the suitability of the CMIP models for this particular variable, the time series of low-pass filtered ensemble mean North American precipitation from the individual CMIP simulations also shows almost no decadal variations. Note especially that the recent observed dry anomalies reside well outside the range of all CMIP runs. This suggests that the models may underestimate the observed variability, at least for North American annual and area averages.

A small number of detection and attribution studies of mean precipitation over land have identified a signal due to volcanic aerosol in low frequency variations of precipitation (Gillett *et al.*, 2004; Lambert *et al.*, 2004). Climate models appear to underestimate both the variance of land mean precipitation compared to that observed and the observed changes in response to volcanic eruptions (Gillett *et al.*, 2004; Lambert *et al.*, 2004). Zhang *et al.* (2007) examined the human influence on precipitation trends over land within latitudinal bands during 1950 to 1999, finding evidence for anthropogenic origins for a drying in the subtropics and increased precipitation over sub-polar latitudes, though observed and simulated anthropogenically forced simulations disagreed over much of North America.

The time series of North America precipitation from the AMIP simulations shows better agreement with that observed than the CMIP simulations, including marked negative anomalies over the last decade. This suggests that a part of the observed low frequency variations stems from observed variations of global SST. A connection between ENSO related tropical SST anomalies and rainfall variability over North America has been well documented, particularly for the boreal winter as mentioned earlier, and the recent years of dryness are consistent with the multi-year occurrence of La Niña (Figure 3.5). The influence of tropical-wide SSTs and droughts in the midlatitudes and North America has also been documented in previous studies (Hoerling and Kumar, 2003; Schubert *et al.*, 2004; Lau *et al.*, 2006; Seager *et al.*, 2005; Herweijer *et al.*, 2006). Such causal links do provide an explanation for the success of AMIP integrations in simulating and explaining some aspects of the observed variability in North American area-averaged precipitation, though it is again important to recognize the limited value of such an area average for describing moisture related climate variations.

3.3 WHAT IS THE PRESENT UNDERSTANDING OF THE CAUSES FOR THE SEASONAL AND REGIONAL DIFFERENCES IN UNITED STATES TEMPERATURE AND PRECIPITATION TRENDS DURING THE REANALYSIS PERIOD?

3.3.1 Introduction

As noted in the recent IPCC Fourth Assessment report, identification of anthropogenic causes for variations or trends in temperature and precipitation at regional and seasonal scales is more difficult than for larger area and annual averages. The primary reason is that internal climate variability is greater at these scales - averaging over larger space-time scales reduces the magnitude of the internal climate variations (Hegerl *et al.*, 2007). Early idealized studies (Stott and Tett, 1998) indicated that the spatial variations of surface temperature changes due to changes in external forcing, such as greenhouse gas related, would be detectable only at scales of order 5000 km or more. But these signals will be more easily detectable as the magnitude of the expected forced response increases with time, and the IPCC Fourth Assessment report highlights the acceleration of the warming response in recent decades (IPCC, 2007a).

Consistent with increased external forcing in recent decades, several studies (Karoly and Wu, 2005; Knutson *et al.*, 2006; Wu and Karoly, 2007; Hoerling *et al.*, 2007) have shown that the warming trends over the second half of the 20th century at many individual five degree latitude/longitude cells across the globe can now be detected in observations, and further, these are consistent with the modeled response to anthropogenic climate forcing and cannot be explained by internal variability and response to natural external forcing alone. However, there are a number of regions that do not show significant warming, including the southeast United States although modeling results have yet to consider a range of other possible forcing factors that may be more important at regional scales including changes in carbonaceous and biogenic aerosols (IPCC, 2007a), and changes in land use and land cover, which affect both the radiative forcing and the partitioning between sensible heating and evaporation at the land surface (Pielke *et al.*, 2002; McPherson, 2007).

What is the current capability to explain spatial variations and seasonal differences in North American climate trends over the past half-century? Can various heterogeneities in space and time be accounted for by the climate system's sensitivity to time evolving anthropogenic forcing? To what extent can the influences of non-anthropogenic processes be identified? Recent studies have linked some regional and seasonal variations in temperature and precipitation over the United States to variations in SST (*e.g.*, Livezey *et al.*, 1997; Kumar *et al.*, 2001; Hoerling and Kumar 2002; Schubert *et al.*, 2004; Seager *et al.*, 2005). These published results have either focused on annual mean or winter-only conditions, and herein we will assess both the winter and summer origins change over North America, the conterminous United States, and various sub-regions of the United States.

3.3.2 Temperature Trends

3.3.2.1 North America

The observed annually-averaged temperature trends over North America in Figure 3.3 of the previous section show considerable spatial variation, with largest warming over northern and western North America and minimum warming over the southeastern United States. The ensemble-mean model response to anthropogenic and natural forcing since 1951 (CMIP runs in Figure 3.3) shows a more uniform warming pattern, with larger values in higher latitudes and in the interior of the continent. While the spatial correlation of the CMIP simulated 1951 to 2006 North American surface temperature trend with observations is 0.79, that agreement results almost entirely from the agreement in the *area-mean* temperature trend. Upon removing the area-mean warming, a process that highlights the spatial variations, the resulting pattern correlation between trends in CMIP and observations reduces to only 0.13. Thus, the spatial variations in observed North American surface temperature change since 1951 are *unlikely* due to anthropogenic forcing alone.

An assessment of AMIP simulations indicates that key features of the spatial variations of annually averaged temperature trends are more consistent with a response to SST variations during 1951 to 2006. The ensemble mean model response to observed SST variations (CMIP runs in Figure 3.3) shows a spatial pattern of North American surface temperature trends that agrees well with the observed pattern - the pattern correlation is 0.87. Upon removing the area-mean warming, the resulting correlation is still 0.57. This indicates that the spatial variation of the observed warming over North America is *likely* influenced by observed regional SST variations, consistent with the previously published results of Robinson *et al.* (2002) and Kunkel *et al.*, (2006).

A diagnosis of observed trends in free atmospheric circulation, using the reanalysis data of 500 mb heights, provides a physical basis for the observed regionality in North American surface temperature trends. Figure 3.7 illustrates the 1951 to 2006 November to April surface temperature trends together with the superimposed 500 mb height trends. It is during the cold half of the year that many of the spatial features in the annual trend originate, a time during which teleconnection patterns are also best developed and exert their strongest impacts. The reanalysis data captures two prominent features of circulation change since 1951, one that projects upon the positive phase of the PNA pattern and the other that projects upon the positive phase of the NAO pattern. Recalling from Chapter 2 the surface temperature fingerprints attributable to the PNA and NAO, the diagnosis in Figure 3.7 reveals that the pattern of observed surface temperature trend can be understood as a linear super-positioning of those fingerprints, consistent with prior published results of Hurrell (1995) and Hurrell (1996).

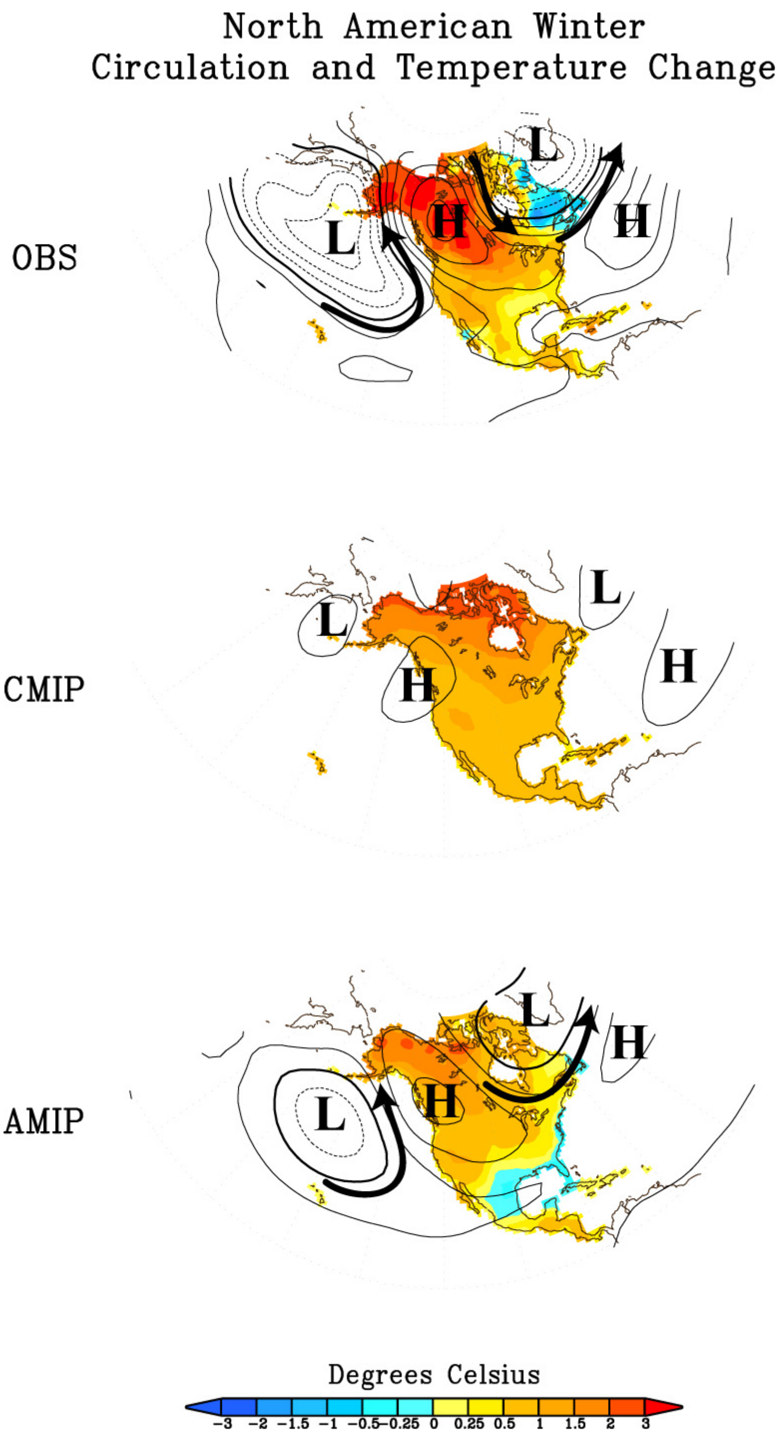

Figure 3.7 The 1951 to 2006 November to April trend of 500 mb heights (contours, units meters/56 years, contour interval 10 m) and North American surface temperature (color shading, units °C/56 years) for observations (top), CMIP ensemble mean(middle), AMIP ensemble mean (bottom). Anomalous High and Low Pressure regions are highlighted. Arrows indicate the anomalous wind direction, which circulates around the High and Low Pressure centers in a clockwise (counterclockwise) direction.

The historical reanalysis data thus proves invaluable for rendering a physically consistent description of the regional structure of North American climate trends. A reason for the inability of the CMIP simulations to replicate key features of the observed spatial variations is revealed by diagnosing their simulated free atmospheric circulation trends, and comparing to the reanalysis data. Shown in the middle panel of Figure 3.7, the CMIP 500 mb height trends have little spatial structure, instead being dominated by a near-uniform increase in heights. Given the strong thermodynamic relation between 500 mb heights and tropospheric column temperature, the relative uniformity of North American surface warming in the CMIP simulations is consistent with the uniformity in its circulation change (there are additional factors that can influence surface temperature patterns, such as local soil moisture, snow cover and sea-ice albedo effects on surface energy balances, that may have little reflection in 500 mb heights).

In contrast, the ability of the AMIP simulations in producing key features of the observed spatial variations in surface temperature stems from the fact that SST variations during 1951 to 2006 force a trend in atmospheric circulation that projects upon the positive phases of both the PNA and NAO patterns (Figure 3.7, bottom panel). Though the amplitude of the ensemble mean AMIP 500 mb height trends is weaker than the observed 500 mb height trends, their spatial agreement is high. It is this wavy aspect to the tropospheric circulation trend since 1951 that permits the reorganization of air mass movements and storm track shifts that is an important factor for explaining key regional details of North American surface climate trends.

3.3.2.2 Conterminous United States

For the United States area-average temperature variations, six of the warmest ten summers (Figure 3.8, top) and 6 of the warmest 10 winters (Figure 3.9, top) during 1951 to 2006 occurred in the last decade (1997 to 2006). This recent clustering of record warm occurrences is consistent with the increasing anthropogenic signal of human induced warming, as evidenced from the CMIP simulations (Figures 3.8 and 3.9, middle panels) that indicate accelerated warming over the United States during the past decade during both summer and winter.

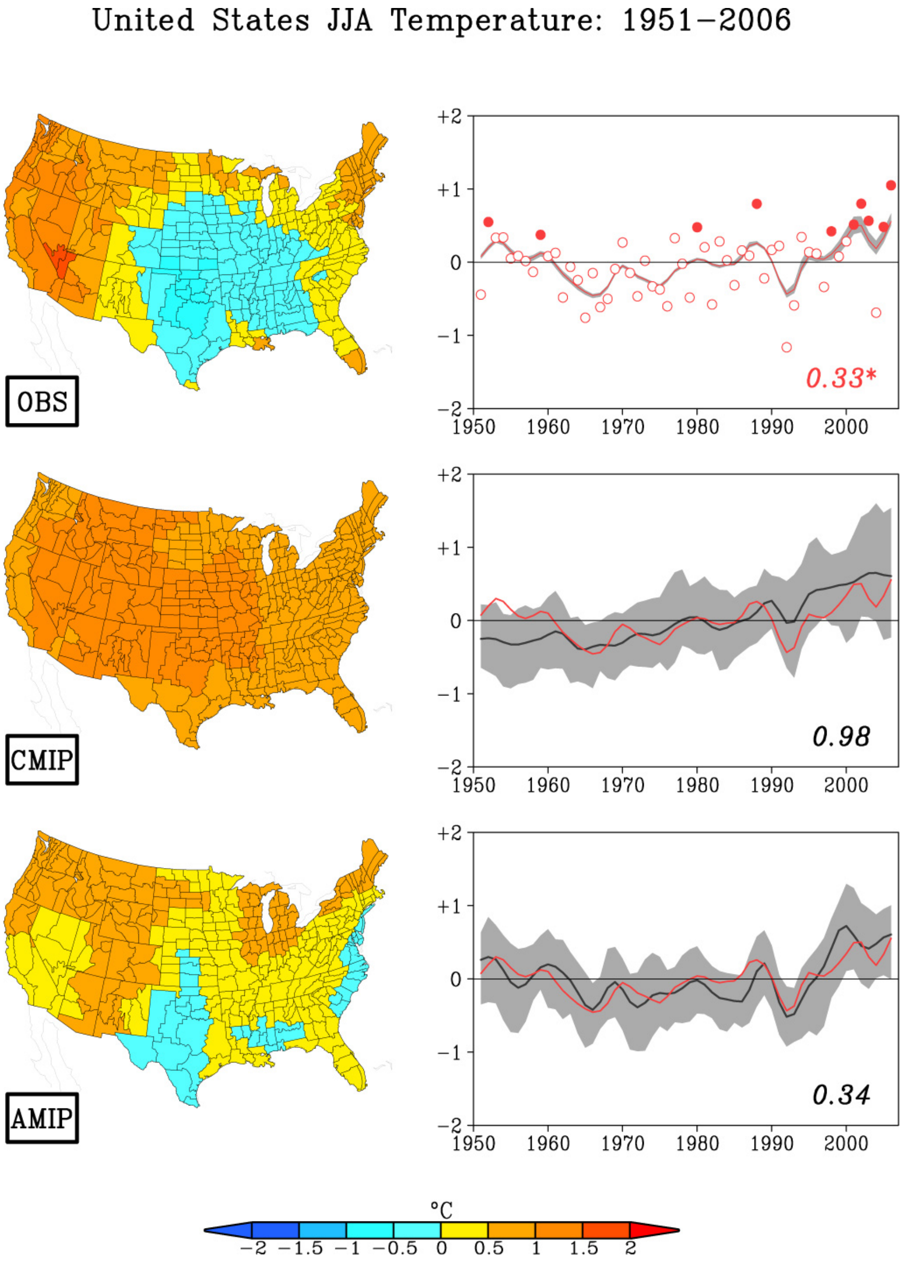

Figure 3.8 Spatial maps of the linear temperature trend (°C/56 years) in summer (June to August) (left side) and time series of the decadal variations of United States area-average temperatures in summer from observations, CMIP model simulations, and AMIP model simulations. Plotted values are the total 56-year change (°C), with the single asterisk denoting high confidence that an observed change was detected Gray band in top panel denotes the range of observed temperatures based on five different analyses, gray band in middle panel denotes the 5-95% range among 41 CMIP model simulations, and gray band in lower panel denotes the 5-95% range among 33 AMIP model simulations. Curves smoothed with 5-point Gaussian filter. Unsmoothed observed annual temperature anomalies shown in open red circles, with warmest 10 years shown in closed red circles.

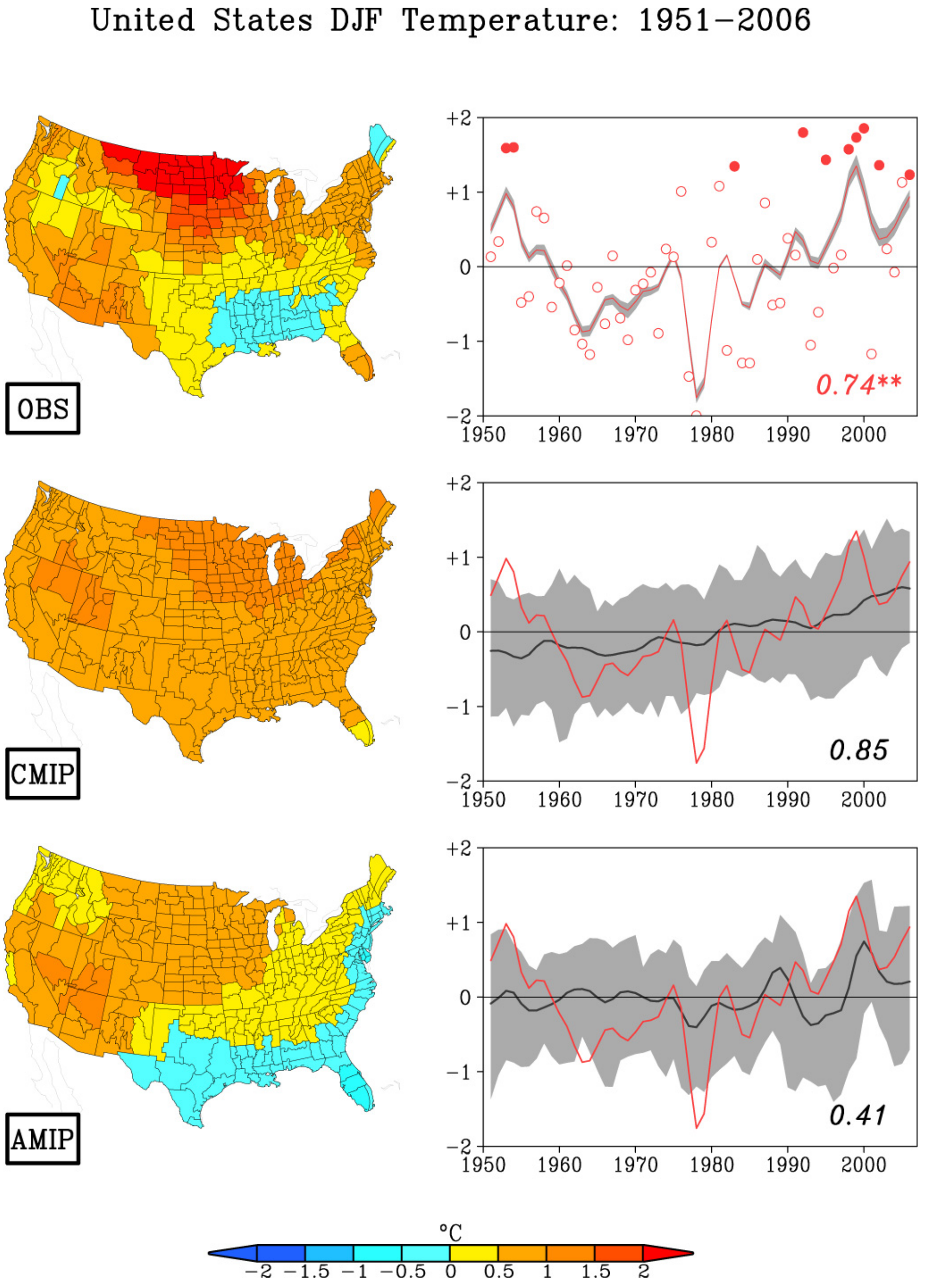

Figure 3.9 Spatial maps of the linear temperature trend (°C/56 years) in winter (December to February) (left side) and time series of the decadal variations of United States area-average temperatures in summer from observations, CMIP model simulations, and AMIP model simulations. Plotted values are the total 56-year change (°C), with the double asterisks denoting very high confidence that an observed change was detected Gray band in top panel denotes the range of observed temperatures based on five different analyses, gray band in middle panel denotes the 5-95% range among 41 CMIP model simulations, and gray band in lower panel denotes the 5-95% range among 33 AMIP model simulations. Curves smoothed with 5-point Gaussian filter. Unsmoothed observed annual temperature anomalies shown in open red circles, with warmest 10 years shown in closed red circles.

During summer, while some regions of the United States have observed strong warming, others experienced no significant change since 1951. The lack of mid-continent warming is a particularly striking feature of the observed trends since 1951, and is juxtaposed with the strong warming in the West. This overall pattern of United States temperature change is *unlikely* due to external anthropogenic forcing alone, an assessment that is supported by several lines of evidence. First, the spatial variations of the CMIP simulated United States temperature trend (Figure 3.8, middle) are uncorrelated with those observed - the pattern correlation is -0.10 when removing the area-mean warming. The ensemble CMIP area-averaged summer warming trend of +0.99°C is also triple the observed area-averaged warming of +0.33°C. In other words, there has been much less summertime warming observed for the United States as a whole than expected based on changes in the external forcing. There is reason to believe - as discussed further below - that internal variations have been masking the anthropogenic warming signal in summer to date, though the possibility that the simulated signal is itself too strong cannot be entirely ruled out.

Second, the spatial variations of the AMIP simulated United States temperature trend (Figure 3.8, bottom) are positively correlated with those observed - the pattern correlation is +0.43 when removing the area-mean warming. The cooling of the southern Plains in the AMIP simulations is in particular agreement with observations, and results in a reduced ensemble AMIP area-averaged United States summer warming trend of only +0.34°C that is close to observations. It thus appears that regional SST variability has played an important role in United States summer temperature trends since 1951. The nature of these important SST variations remains unknown. The extent to which they are due to internal coupled system variations and the contribution from anthropogenic forcing are among the vital questions awaiting future attribution research.

During winter, the pattern of observed surface temperature trends (Figure 3.9, top) consists of strong and significant warming over the West and North, and insignificant change along the Gulf Coast. Both CMIP and AMIP simulations produce key features of the United States temperature trend pattern (spatial correlations of 0.70 and 0.57 respectively upon removing the United States area-mean warming trend), though the cooling along the Gulf Coast appears inconsistent with external forcing, but consistent with SST forcing. The observed United States winter warming trend of +0.75°C has been stronger than that occurring in summer, and compares to an area-averaged warming of +0.85°C in the ensemble of CMIP and +0.41°C in the ensemble of AMIP simulations.

It is worth noting that the United States also experienced warm conditions during the mid-20th century - the early years of available reanalyses (see also Box 3.3 for discussion of the United States warmth in the early 20th century). It is partly for this reason that the 1951 to 2006 observed trends, especially during summer, are not greater. This is an indication for the sensitivity of trends to the beginning and end-years selected for diagnosis, and requires that the trend analysis be accompanied by an assessment of the full temporal evolution during 1951 to 2006.

Regarding confidence levels for the observed United States temperature trends for 1951 to 2006, a non-parametric test has been applied that estimates the probability distribution of 56-year trends attributable to natural variability alone (see Appendix 3.A for methodological details). As in Section 3.2, this involves diagnosis of 56-year trends from the suite of "naturally forced" CMIP runs, from which a sample of 76 such trends were generated for the conterminous United States for winter and summer seasons. The observed area-averaged United States summer trend of +0.33°C is found to exceed the 80% level of trend occurrences in those natural forced runs, indicating a *high* level of confidence that warming has been detected. For winter, the observed trend of +0.75°C is found to exceed the 95% level of trends in the natural forced runs indicating a *very high* level of confidence. These diagnoses support our assessment that a warming of United States area-averaged temperatures during 1951 to 2006 has likely been detected for summer and very likely been detected for winter.

The causes of the reduced warming in the southeast United States, seen during both winter and summer seasons, relative to the remainder of the country have been considered in several studies. Knutson *et al.* (2006) contrasted the area-average temperature variations for the southeast United States with those for the remainder of the United States (as shown in Figure 3.10) for both observations and model simulations with the GFDL CM2 coupled model. While the observed and simulated warming due to anthropogenic forcing agrees well for the remainder of the United States, the observed cooling is outside the range of the small ensemble considered. For a larger ensemble, such as the whole CMIP multi-model ensemble, as considered by Kunkel *et al.* (2006), the cooling in the southeast United States is within the range of model simulated temperature variations but would have to be associated with a very large case of natural cooling superimposed on anthropogenically-forced larger scale warming. Robinson *et al.* (2002) and Kunkel *et al.* (2006) have shown that this regional cooling in the central and southeast United States is associated with the model response to observed

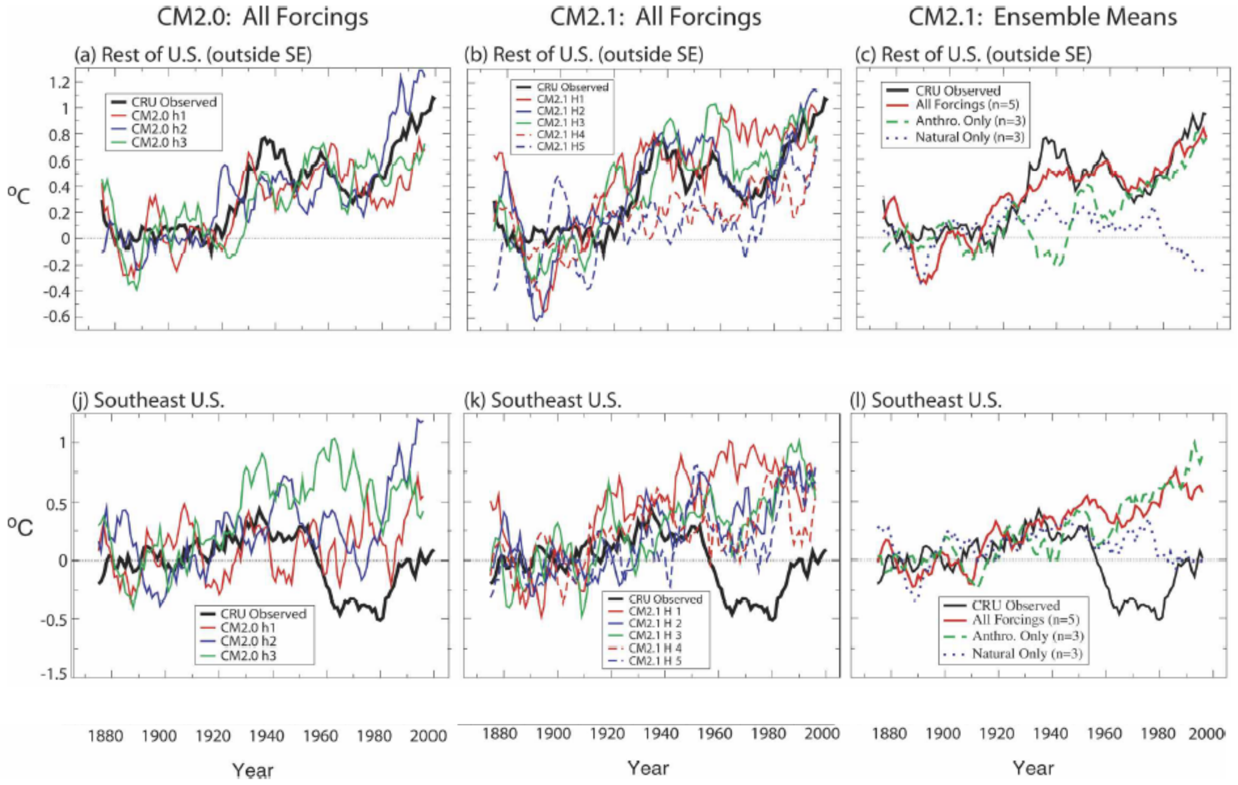

Figure 3.10 Ten-year running-mean area-averaged time series of surface temperature anomalies (°C) relative to 1881 to 1920 for observations and models for various regions: (a)–(c) rest of the contiguous United States, and (j)-(l) southeast United States. The left column and middle columns are based on all-forcing historical runs 1871–2000 and observations 1871 to 2004 for GFDL coupled climate model CM2.0 (n _ 3) and CM2.1 (n _ 5), respectively. The right column is based on observed and model data through 2000, with _2 standard error ranges (shading) obtained by sampling several model runs according to observed missing data. The red, blue, and green curves in the right-hand-column diagrams are ensemble mean results for the CM2.1 all-forcing (n _ 5), natural-only (n _ 3), and anthropogenic-only (n _ 3) forcing historical runs. Model data were masked according to observed data coverage. From Knutson *et al.*, (2006).

SST variations, particularly in the tropical Pacific and North Atlantic oceans, and is consistent with the additional assessment of AMIP simulations presented in this Section. For the winter half of year in particular, the southeast cooling is also consistent with the trends in teleconnection patterns that were diagnosed from the reanalysis data.

Other studies have argued that land use and land cover changes are additional candidate factors for explaining the observed spatial variations of warming over the United States since 1951. The marked increase of irrigation in the central valley of California and the northern Great Plains is likely to have lead to a warming of minimum temperatures and a reduced warming of maximum temperatures in summer (Christy *et al.*, 2006; Kueppers *et al.*, 2007; Mahmood *et al.*, 2006). Urbanization, land clearing, deforestation and reforestation are likely to have contributed to some of the spatial patterns of warming over the United States, though a quantification of these factors is lacking (Hale *et al.*, 2006; Kalnay and Cai, 2003; Trenberth, 2004; Vose, 2004; Kalnay *et al.*, 2006).

As a further assessment of the spatial structure of temperature variations, the 1951 to 2006 summer and winter surface temperature time series for nine United States sub-regions are shown in Figure 3.11 and 3.12, respectively. The observed time series is shown by the red bold curve, and the CMIP and AMIP ensemble mean time series are superimposed with blue and green curves, respectively. No attribution of recent climate variations and trends at these scales has been published, aside from the aforementioned

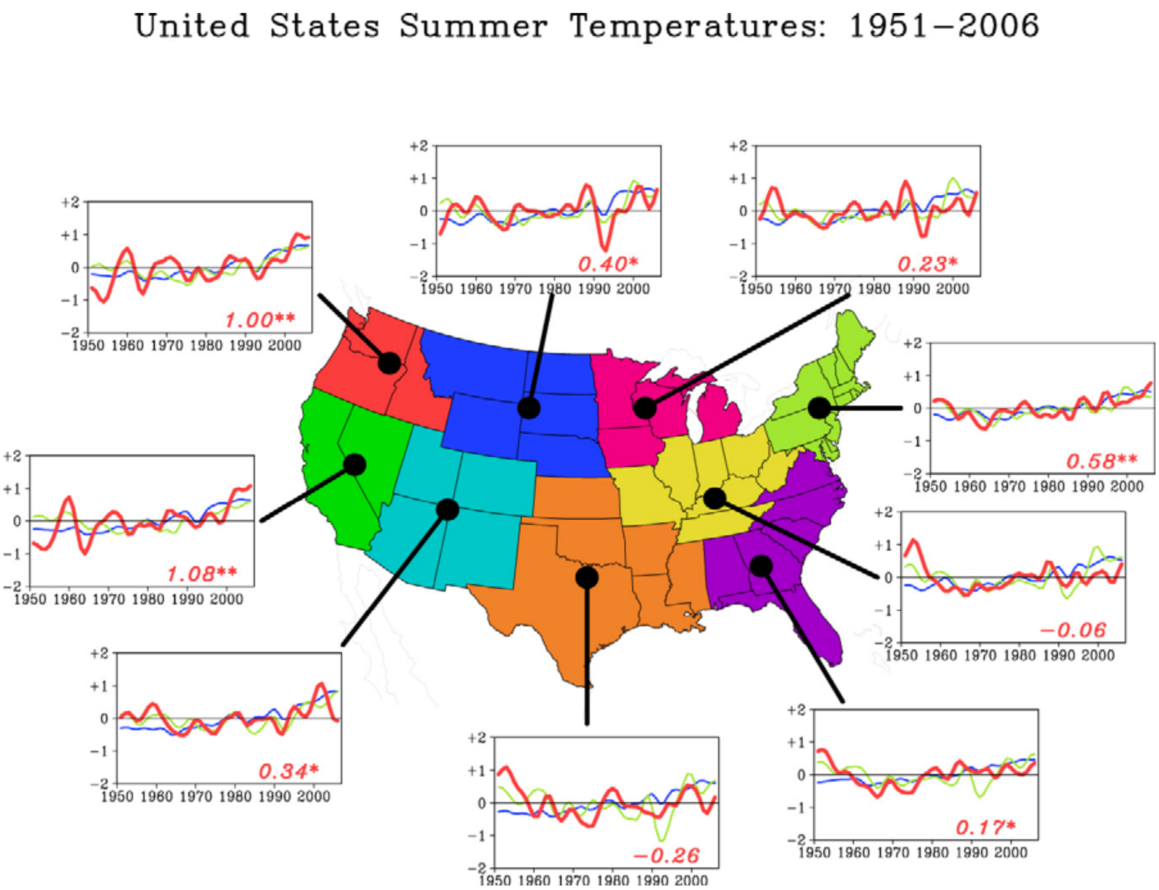

Figure 3.11 The 1951 to 2006 time series of regional United States surface temperatures in summer (June to August). The observations are shown in bold red, ensemble mean CMIP in blue, and ensemble mean AMIP in green. A 5-point Gaussian filter has been applied to the time series to emphasize multi-annual scale time variations. Plotted values in each graph indicate the total 1951 to 2006 temperature change averaged for the sub-region. Double (single) asterisks denote regions where confidence of having detected a change is very high (high).

Knutson *et al.* (2006) and Kunkel *et al.* (2006) studies that examined conditions over the southeast United States. In so far as decision making occurs on these regional scales, and smaller local scales, the need for a systematic explanation of such climate conditions is needed. Here we comment only upon several salient features of the observed and simulated changes, but stress that a complete synthesis has yet to be undertaken. For each region

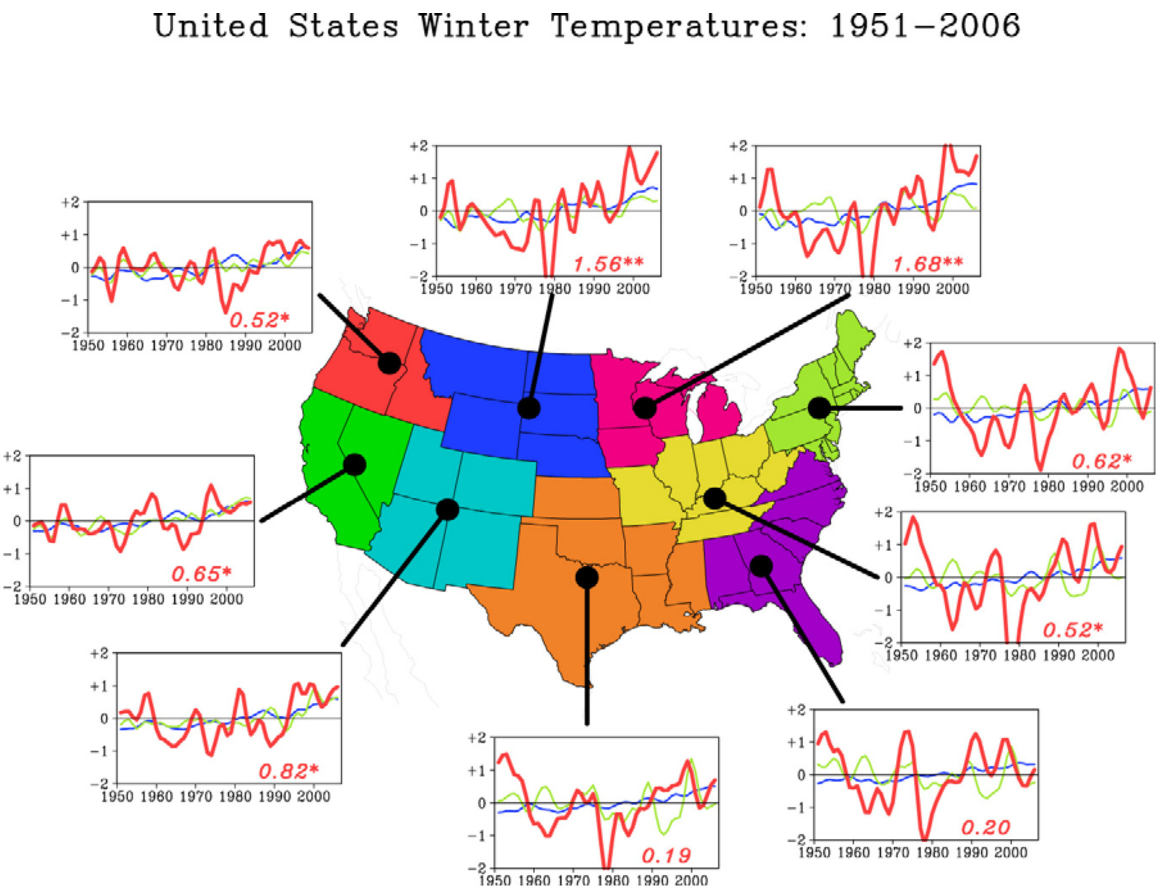
United States Winter Temperatures: 1951–2006

Figure 3.12 The 1951 to 2006 time series of regional United States surface temperatures in winter (December to February). The observations are shown in bold red, ensemble mean CMIP in blue, and ensemble mean AMIP in green. A 5-point Gaussian filter has been applied to the time series to emphasize multi-annual scale time variations. Plotted values in each graph indicate the total 1951 to 2006 temperature change averaged for the sub-region. Double (single) asterisks denote regions where confidence of having detected a change is very high (high).

of the United States, the total 1951 to 2006 observed surface temperature change and its significance is plotted beneath the time series. Single and double asterisks denote high and very high confidence, respectively, that a change has been detected using the methods described above.

During summer (Figure 3.11), there exists *very high* confidence that warming has been observed over Pacific Northwest and Southwest regions. For these, the net warming since

1951 has been about +1°C, exceeding the 95% level of trends in the natural forced runs at these regional scales. *High* confidence of a detected warming also exists for the Northeast, where the observed 56-year change is not as large, but occurs in a region of reduced variability thereby enhancing detectability of a change. These three warming regions also exhibit the best temporal agreement with the warming simulated in the CMIP models. It is also noteworthy that the comparatively weaker observed summertime trends during 1951 to 2006 in the interior West, the southern Great Plains, the Ohio Valley, and the southeast United States results from the very warm conditions at the beginning of the reanalysis record, a period of widespread drought in those regions of the country.

During winter (Figure 3.12), there is *very high* confidence that warming has been detected over the Northern Plains and Great Lakes region. Confidence is *high* that warming during 1951 to 2006 has been detected in the remaining regions, except along the Gulf Coast where no detectable change in temperature has occurred. In the northern regions, most of the net warming of about +1.5°C has happened in the recent two decades. It is noteworthy that the CMIP simulations also produce accelerated winter warming over the northern United States in the past 20 years, suggesting that this regional and seasonal feature may have been influenced by anthropogenic forcing.

The 1950s produced some of the warmest winters during the 1951 to 2006 period for several regions of the United States. The latest decade of surface warmth in the four southern and eastern United States regions still fails to exceed that earlier decadal warmth. The source for the warm winters in those regions in mid-century is not currently known, and it is unclear whether it is related to a widespread warm period across the Northern Hemisphere during the 1930s and 1940s that was attributed primarily to internal variability (Delworth and Knutson, 2000). The fact that neither CMIP nor AMIP ensemble mean responses produce such 1950s warmth supports an interpretation that the United States 1950s warmth was likely unrelated to external or the SST forcing.

3.3.3 Precipitation Trends

3.3.3.1 North America

The observed annual North American precipitation trends during 1951 to 2006 in Figure 3.6 of the previous Section are dominated by regional scale features. Of the identifiable features of change, prominent is the annual drying of Mexico and the greater Caribbean region, and the increase over northern Canada. However, owing to the strong and disparate seasonal cycles of precipitation across the continent, a diagnosis of the annual mean trends is of limited value. We thus focus further discussion on the seasonal and regional analyses below.

Shown in Figure 3.13 (top) is the cold-season (November to April) North American observed precipitation change, with superimposed contours of the tropospheric circulation change (identical to Figure 3.7). The reanalysis data of circulation change provides physical insights on the origins of the observed regional precipitation change. The band of drying that extends from British Columbia across much of southern Canada and part of the northern United States corresponds to upper level high pressure from which one can infer reduced storminess. In contrast, increased precipitation across the southern United States

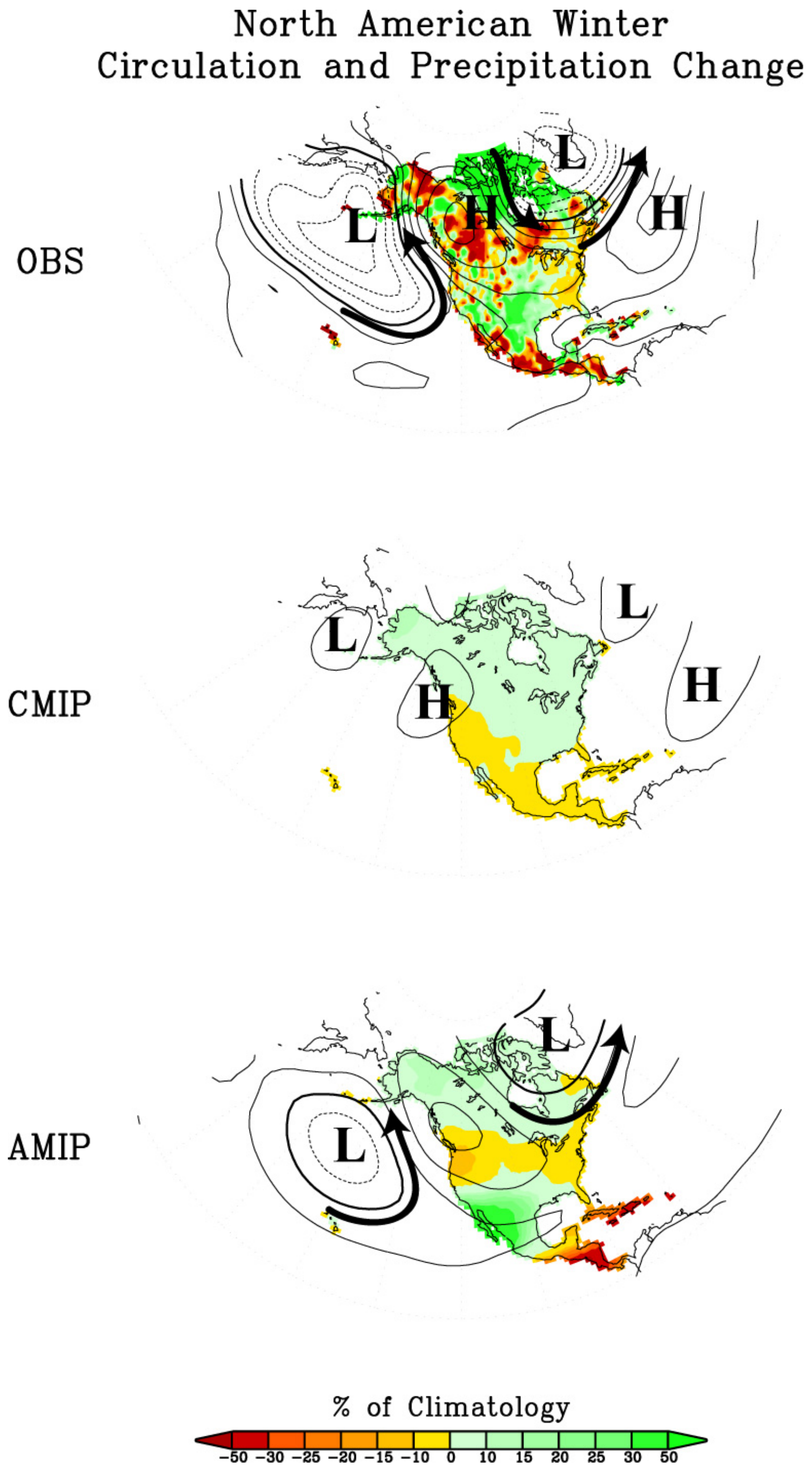

Figure 3.13 The 1951 to 2006 November to April trend of 500 mb heights (contours, units meters/56 years, contour interval 10 m) and North American precipitation (color shading, units 56-year change as % of climatology) for observations (top), CMIP ensemble mean (middle), AMIP ensemble mean (bottom). Anomalous High and Low Pressure regions are highlighted. Arrows indicate the anomalous wind direction, which circulates around the High and Low Pressure centers in a clockwise (counterclockwise) direction.

and northern Mexico in winter is consistent with the deeper southeastward shifted Aleutian low that is conducive for increased winter storminess across the southern region of the United States. Further south, drying again appears across southern Mexico and Central America. This regional pattern is unrelated to external forcing alone, as revealed by the lack of spatial agreement with the CMIP trend pattern (middle panel), and the lack a wavy tropospheric circulation response in the CMIP simulations. Many key features of the observed regional precipitation change are, however, consistent with the forced response to global SST variations during 1951 to 2006, as is evident from the AMIP trend pattern (bottom). In particular, the AMIP simulations generate the zonal band of enhanced high latitude precipitation, the band of reduce precipitation centered along 45°N, wetness in the southern United States and North Mexico, and dryness over Central America. These appear to be consistent with the SST forced change in tropospheric circulation. It is thus again important to determine, in future attribution research, the responsible regional SST variations, and to assess the origin of the SSTs anomalies themselves.

3.3.3.1 Conterminous United States

The observed seasonal-mean precipitation trends over the period 1951 to 2006 are compared with the ensemble mean responses of the CMIP and AMIP simulations for summer in Figure 3.14 and for winter in Figure 3.15. During all seasons in general, there are smaller scale spatial variations of the observed precipitation trends across the United States than for the temperature trends, and larger interannual and decadal variability. These factors undermine the detectability of any physical change in precipitation since 1951.

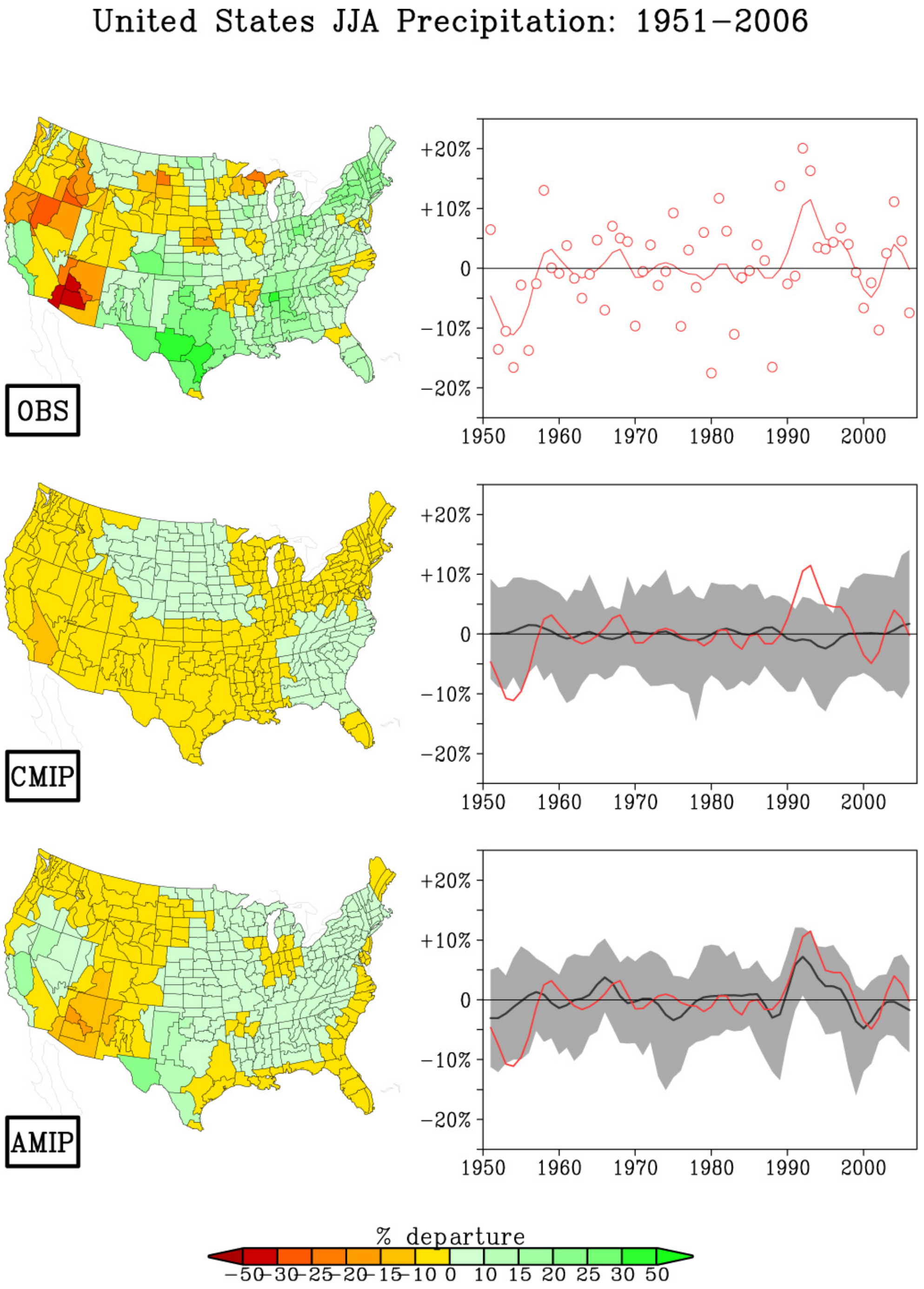

Figure 3.14 Spatial maps of the linear trend in precipitation (% change of seasonal climatology) in summer (June through August) (left side) and time series of the decadal variations of United States area-average precipitation in summer from observations, CMIP model simulations, and AMIP model simulations. Gray band in middle panel denotes the 5-95% range among 41 CMIP model simulations, and gray band in lower panel denotes the 5-95% range among 33 AMIP model simulations. Curves smoothed with 5-point Gaussian filter. Unsmoothed observed annual precipitation anomalies shown in open red circles.

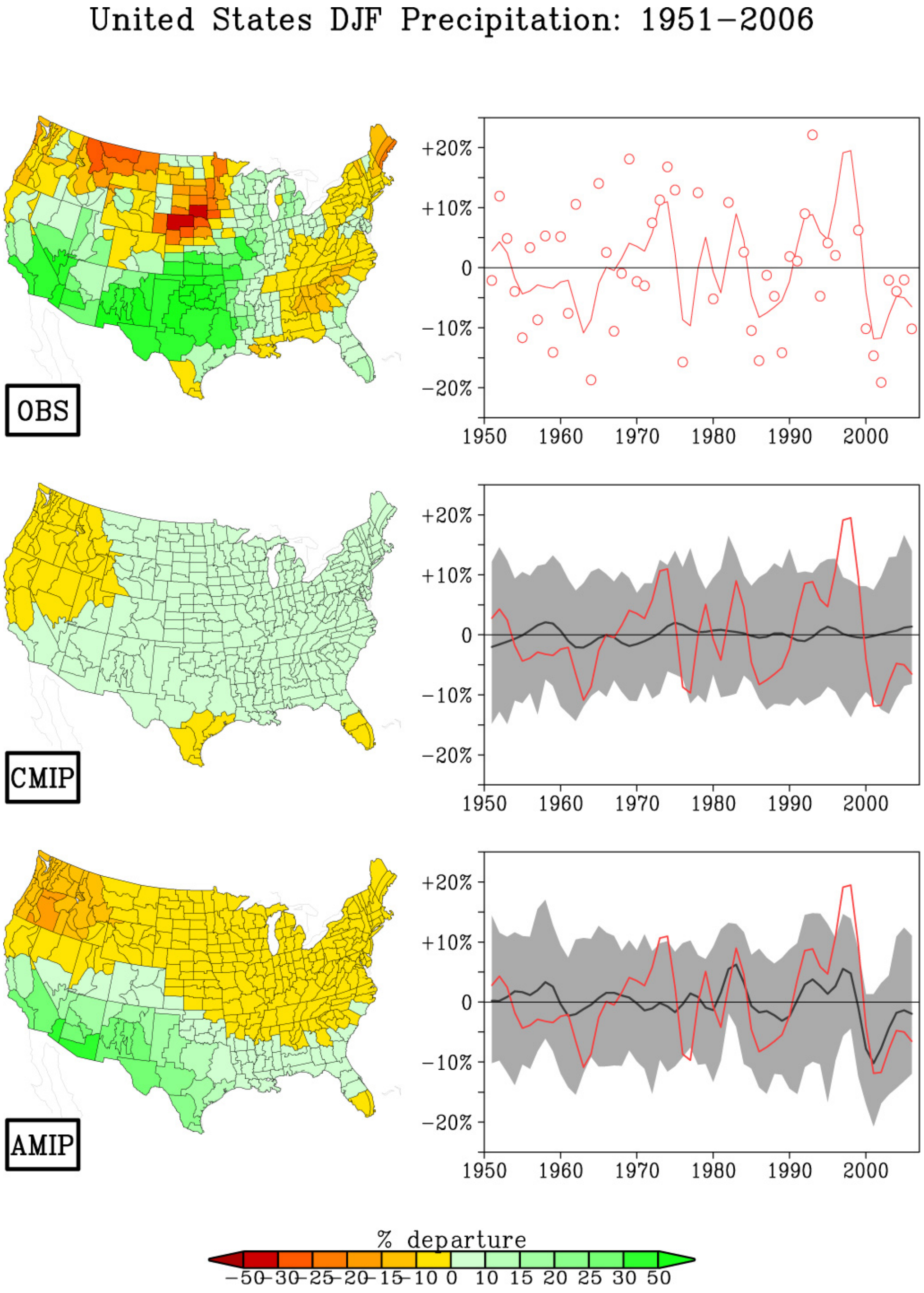

Figure 3.15 Spatial maps of the linear trend in precipitation (% change of seasonal climatology) in winter (December through February) (left side) and time series of the decadal variations of United States area-average precipitation in winter from observations, CMIP model simulations, and AMIP model simulations. Gray band in middle panel denotes the 5-95% range among 41 CMIP model simulations, and gray band in lower panel denotes the 5-95% range among 33 AMIP model simulations. Curves smoothed with 5-point Gaussian filter. Unsmoothed observed annual precipitation anomalies shown in open red circles.

During summer (Figure 3.14), there is a general pattern of observed rainfall reductions in the west and southwest United States and increases in the east. There is some indication of similar patterns in the CMIP and AMIP simulations, however, the amplitudes are so weak that the ensemble model anomalies are themselves unlikely to be significant. The time series of United States summer rainfall is most striking for a recent fluctuation between wet conditions in the 1990s, followed by dry conditions in the late 1990s and early 2000s. This prominent variation is well explained by the region's summertime response to SST variations, as seen by the remarkable correspondence of observations with the time evolving AMIP rainfall (lower panel). For the 56-year period as a whole, the temporal correlation of AMIP simulated and observed summer United States averaged rainfall is +0.64.

During winter (Figure 3.15), there is little agreement between the observed and CMIP modeled spatial patterns of trends, though considerably better agreement exists with the AMIP modeled spatial pattern. Again, the ensemble mean CMIP model simulations shows no significant long term trends during 1951 to 2006, and they also exhibit muted variability (middle), suggesting that changes in external forcing have had no appreciable influence on area-average precipitation in the United States. This is consistent with the published results of Zhang *et al.* (2007) who find disagreement between observed and CMIP simulated trends over the United States. In contrast, several key decadal variations are captured by the ensemble mean AMIP simulations including again the swing from wet 1990s to dry late 1990s early 2000 conditions. For the 56-year period as a whole, the temporal correlation of AMIP simulated and observed winter United States averaged rainfall is +0.59.

For the nine separate United States regions, Figures 3.16 and 3.17 illustrate the temporal variations of observed, ensemble CMIP, and ensemble AMIP precipitation for summer and winter seasons, respectively. These highlight the strong temporal swings in observed regional precipitation between wet and dry periods, such that no single region has a detectable change in precipitation during 1951 to 2006. These observed fluctuations are nonetheless of great societal relevance, being associated with floods and droughts having catastrophic local impacts. Yet, comparing to CMIP simulations indicates that it is *exceptionally unlikely* that these events are related to external forcing. There is some indication from the AMIP simulations that their occurrence is somewhat determined by SST events especially in the south and west during winter presumably related to the ENSO cycle.

It should be noted that other statistical properties of rainfall, including extremes in daily amounts and the fraction of annual rainfall due to individual wet days have exhibited a detectable change over the United States in recent decades, and such changes have been attributed to anthropogenic forcing in the companion CCSP SAP 3.3 report (CCSP, in press).

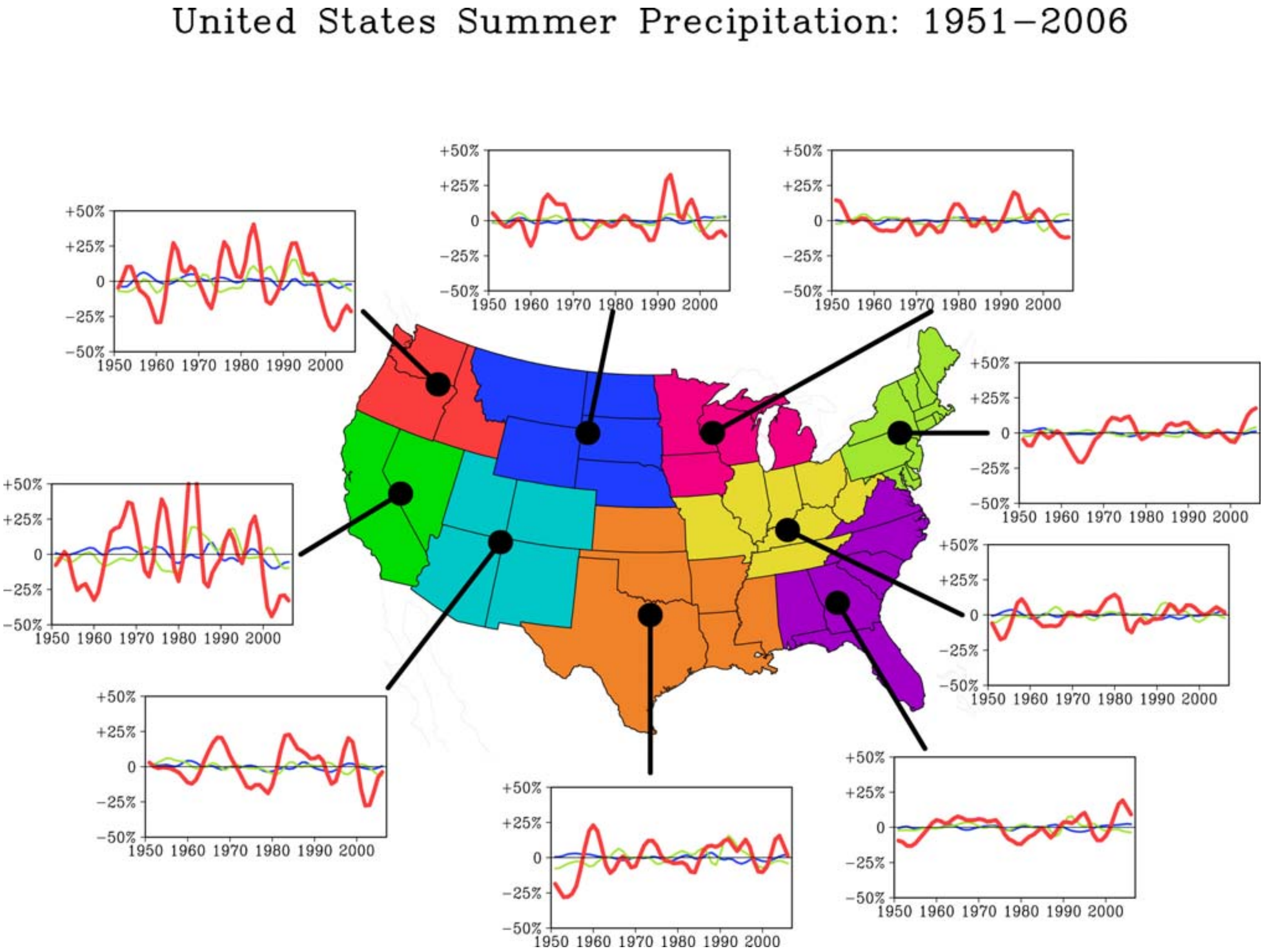

Figure 3.16 The 1951 to 2006 time series of regional United States precipitation in summer (June through August). The observations are shown in bold red, ensemble mean CMIP in blue, and ensemble mean AMIP in green. A 5-point Gaussian filter has been applied to the time series to emphasize multi-annual scale time variations.

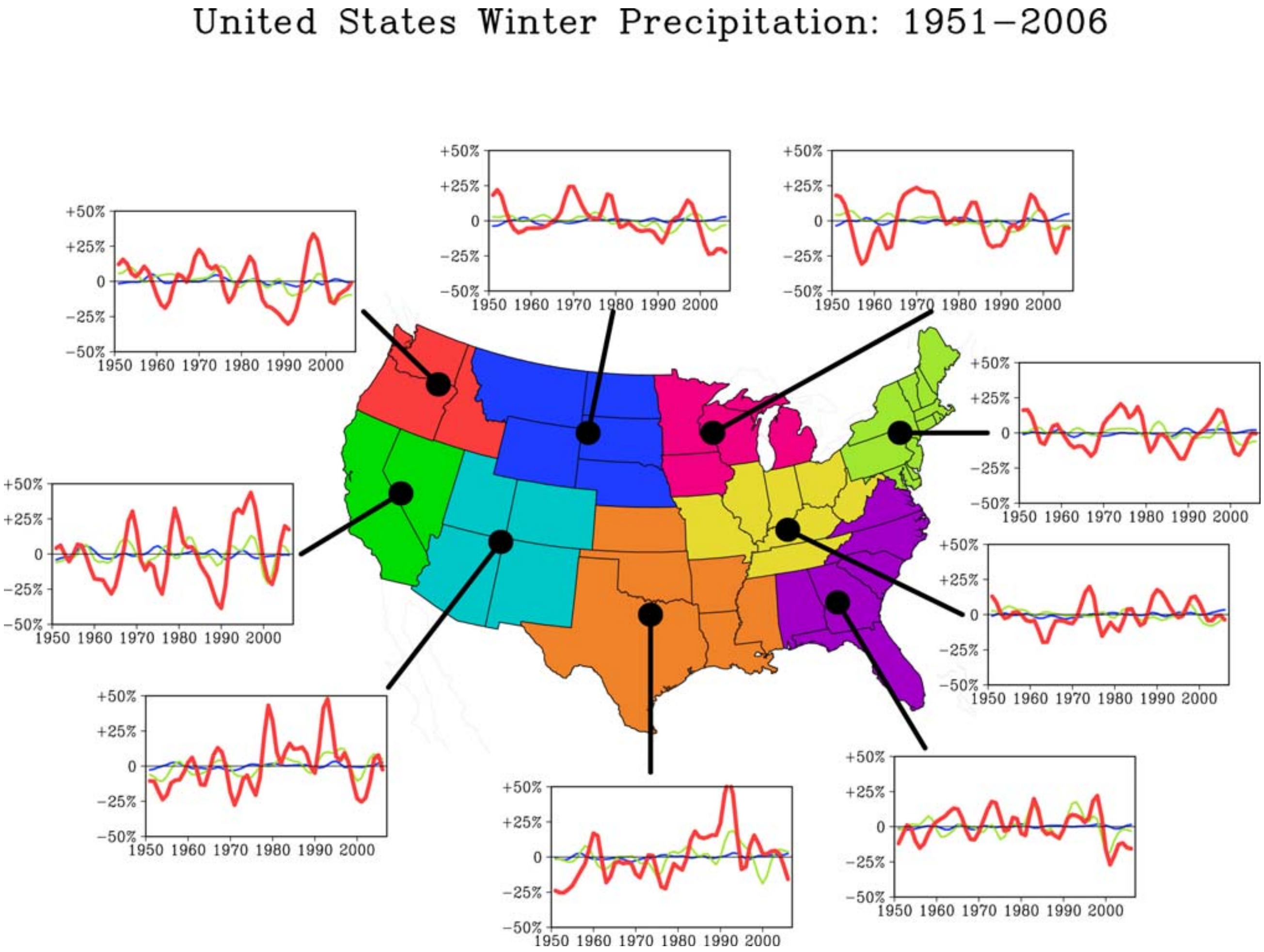

Figure 3.17 The 1951 to 2006 time series of regional United States precipitation in winter (December to February). The observations are shown in bold red, ensemble mean CMIP in blue, and ensemble mean AMIP in green. A 5-point Gaussian filter has been applied to the time series to emphasize multi-annual scale time variations.

3.4 WHAT IS THE NATURE AND CAUSE OF APPARENT RAPID CLIMATE SHIFTS, HAVING MATERIAL RELEVANCE TO NORTH AMERICA, OVER THE REANALYSIS PERIOD?

3.4.1 Introduction

Rapid climate shifts are of scientific interest and of public concern because of the expectation that such occurrences may be particularly effective in exposing the vulnerabilities of societies and ecosystems (Smith *et al.*, 2001). Such abrupt shifts are typically distinguished from the gradual pace of climate change associated, for instance, with anthropogenic forcing. However, through non-linear feedbacks the latter could also trigger rapid shifts in some parts of the climate system, a frequently cited example being a possible collapse of the global ocean's principal conveyor of heat between the tropics and high latitudes known as the thermohaline circulation (Clarke *et al.*, 2002).

By their very nature, abrupt shifts are unexpected events - climate surprises - and thus offer particular challenges to policy makers in planning for their impacts. A retrospective assessment of such "rare" events may offer insights on mitigation strategies that are consistent with the severity of impacts related to rapid climate shifts. Such an assessment would also consider impacts of abrupt climate shifts on societies and ecosystems and would also prepare us to anticipate consequences of gradual changes in climate, in so far as they may be no less severe than those related to rapid climate shifts.

3.4.2 Defining Rapid Climate Shifts

A precise definition for a climate shift that is either "rapid" or "abrupt" does not exist owing to limited knowledge about the full sensitivity of the climate system. For instance, due to nonlinearity, changes in external forcing need not lead to a proportionate climate response. It is conceivable that a *gradual* change in external forcing could yield an abrupt response when applied near a tipping point of sensitivity in the climate system, whereas an *abrupt* change in forcing may not lead to any abrupt response when it is applied far from the system's tipping point between various equilibrium climate states. To date, little is known about the threshold tipping points of the climate system (Alley *et al.*, 2003).

In its broadest sense, a "rapid" shift is a transition between two climatic states that individually have much longer duration than the transition period itself. From an impacts viewpoint, a rapid climate shift is one occurring so fast that societies and ecosystems have difficulty adapting to it.

3.4.3 Mechanisms for Rapid Climate Shifts

The National Research Council (NRC, 2002) has undertaken a comprehensive assessment of rapid climate change, summarizing evidence of such changes occurring before the instrumental and reanalysis records, and understanding abrupt changes in the modern era. The NRC (2002) report on abrupt climate change draws attention to evidence for severe swings in climate proxies of temperature (so-called paleo-reconstructions) during both the last ice age and the subsequent interglacial period known as the Holocene. Ice core data indicate that abrupt shifts in climate have often occurred during Earth's climate history, indicating that gradual and smooth movements do not always characterize climate variations. Identification of such shifts is usually empirical, based upon expert assessment of long time series of the relevant climate records, and in this regard their recognition is usually retrospective. Against this background of abundant evidence for the magnitude of rapid climate shifts, there is a dearth of information about the mechanisms that can lead to climate shifts and of the processes by which climate states are maintained in their altered states (Broecker, 2003). Understanding the causes of such shifts is a prerequisite to any early warning system that is, among other purposes, needed for planning the scope and pace of mitigation.

The National Academy report also highlights three candidate mechanisms for abrupt change: (1) an abrupt forcing, such as may occur through meteorite impacts or volcanic eruptions, (2) a threshold-like sensitivity of the climate system in which sudden changes can occur even when subjected to gradual changes in forcing, (3) an unforced behavior of the climate system resulting purely from chaotic internal variations.

3.4.4 Rapid Climate Shifts since 1950

Although changes in external forcing, whether natural or anthropogenic, are not yet directly assimilated in the current generation of reanalysis products, abrupt changes in external forcings can still influence the reanalyses indirectly thru their effect on other assimilated variables. Observational analyses of the recent instrumental record gives some clues of sudden climate shifts, ones having known societal consequences. These are summarized below according to the current understanding of the potential mechanism involved. For several reasons, the sustainability of these apparent shifts is not entirely known. First, multi-decadal fluctuations are readily seen in post-1950 North American time series of temperature (Figure 3.3) and precipitation (Figure 3.6). Although the post-1950 period is the most accurately observed period of Earth's climate history, the semi-permanency of any change cannot be readily judged from merely 50 years of data. This limited perspective of our brief modern climate record stands in contrast to proxy climate records within which stable climate was punctuated by abrupt change leading to new climate states lasting centuries to millennia. Second, it is not known whether any recent rapid transitions have involved threshold accidences in a manner that would forewarn of their permanence.

3.4.4.1 Abrupt natural external forcings since 1950

The period of the reanalysis record was a volcanically active one, particularly when compared to the first half of the 20th century. Three major eruptions included the Agung, El Chichon, and Pinatubo volcanoes of 1963, 1982, and 1991, respectively. Each of these injected aerosols into the stratosphere acting to significantly increase the stratospheric aerosol optical depth that led to an increase in the reflectance of incoming solar radiation (Santer *et al.*, 2006).

Each of these abrupt volcanic forcings has been found to exert a discernable impact on climate conditions. Observed sea surface temperatures cooled in the wake of the eruptions, the detectability of which was largest in oceans having small unforced, internal variability (Santer *et al.*, 2006). Surface based observational analyses of these and other historical volcanoes indicates North American surface temperatures tend to experience warming in the winters following strong eruptions, but cooling in the subsequent summer (Kirchner *et al.*, 1999). These abrupt forcings have not, however, led to sustained changes in climate conditions, in so far as the residence time for the stratospheric aerosol increases due to volcanism is less than a few years (depending on the particle distributions and the geographical location of the volcanic eruption), and the fact that major volcanic events since 1950 have been well separated in time.

The impact of the volcanic events is readily seen in Figure 3.18 (green curve) which plots time series of annual SSTs in various ocean basins derived from the ensemble mean CMIP simulations forced externally by estimates of the time evolving volcanic and solar forcings - so-called “natural forcing” runs. The SST cooling in the wake of each event is evident. Furthermore, in the comparison with SST evolutions in the fully forced natural and anthropogenic CMIP runs (Figure 3.18, bars), the lull in ocean warming in the early 1980s and early 1990s was likely the result of the volcanic aerosol effects. Similar lulls in warming rates are evident in the observed SSTs at these times (Figure 3.5). They are also evident in the observed and CMIP simulated North American surface temperature time series (Figure 3.3). Yet, while having detected the climate system’s response to abrupt forcing, and while some model simulations detect decadal-long reductions in oceanic heat content following volcanic eruptions (Church *et al.*, 2005), their impacts on surface temperature have been relatively brief and transitory.

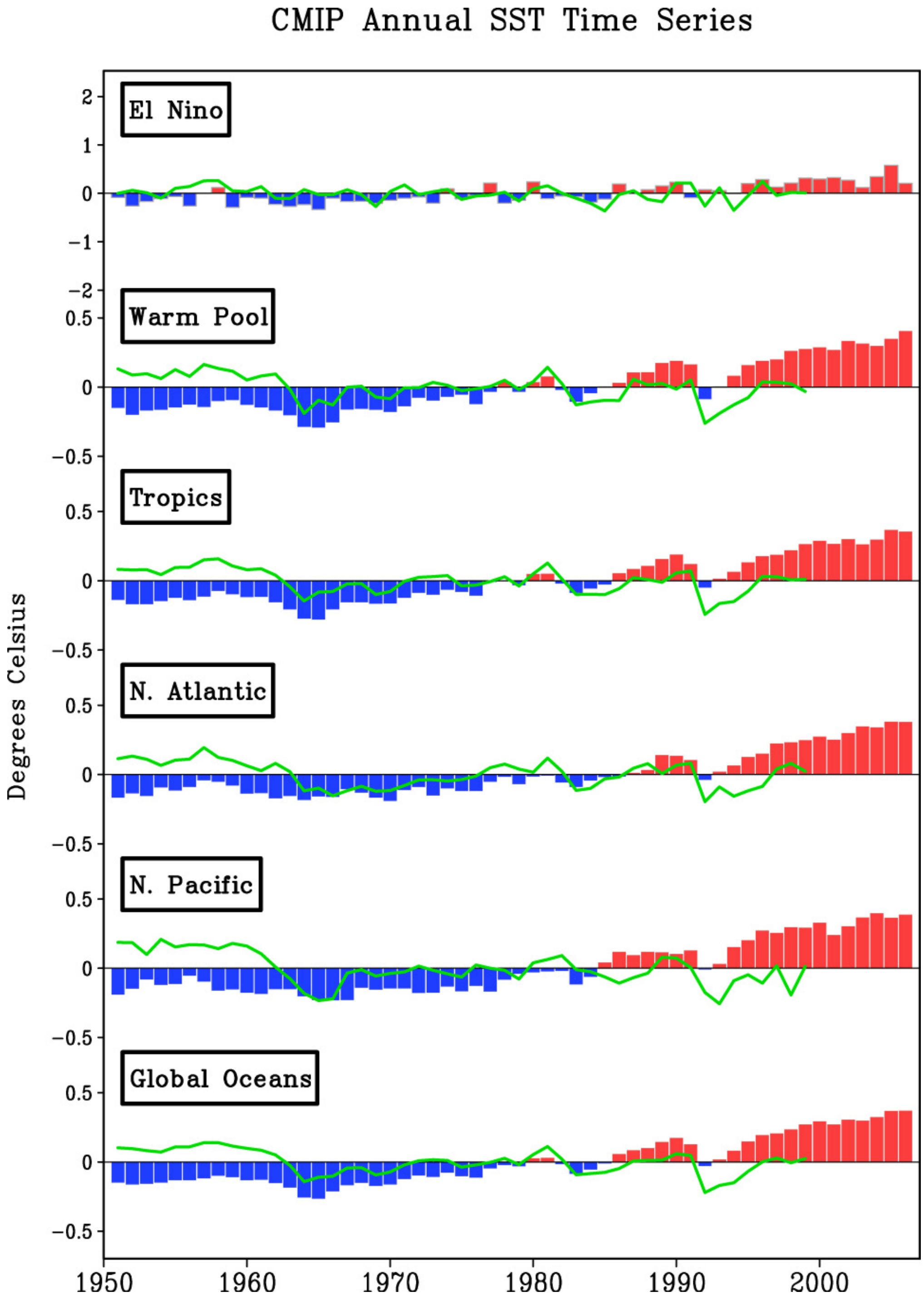

Figure 3.18 CMIP simulated annual mean SST time series for 1951 to 2006. The oceanic regions used to compute the indices are 5°N-5°S, 90°W-150°W for El Niño, 10°S-10°N, 60°E-150°E for the warm pool, 30°S-30°N for the tropics, 30°N-60°N for the North Atlantic, 30°N-60°N for the North Pacific, and 40°S-60°N for the global oceans. Data set is the ensemble mean of 19 CMIP models subjected to the combination of external anthropogenic and natural forcing , and anomalies are calculated relative to each model's 1951 to 2006 reference. Green curve is the surface temperature time series based on the ensemble mean of four CMIP models forced only by time evolving natural forcing (volcanic and solar).

3.4.4.2 Abruptness related to gradual increase of greenhouse gases since 1950

Has the gradual increase in greenhouse gas external forcing triggered threshold-like behavior in climate, and what has been the relevance for North America? There is evidence of abrupt changes of ecosystems in response to anthropogenic forcing that is consistent with tipping point behavior over North America (Adger *et al.*, 2007), and some elements of the physical climate system including sea ice, snow cover, mountainous snow pack, and streamflow have also exhibited rapid change in recent decades (IPCC, 2007a).

There is also some suggestion of abrupt change in ocean surface temperatures. Whereas the net global radiative forcing due to greenhouse gas increases has increased steadily since 1950 (IPCC, 2007a), observed sea surface temperature over the warmest regions of the world ocean - the so-called warm pool - have experienced a rapid shift to warm conditions in the late 1970s (Figure 3.5). In this region covering the Indian Ocean and western tropical Pacific Ocean where surface temperatures can exceed 30°C, the noise of internal SST variability is weak, increasing the confidence in the detection of change. While there is some temporal correspondence between the rapid 1970s emergent warm pool warming in observations and CMIP simulations (Figure 3.18), further research is required to confirm that a threshold-like response of the ocean surface heat balance to steady anthropogenic forcing occurred.

The matter of the relevance of abrupt oceanic warming for North American climate is even less clear. On the one hand, North American surface temperatures also warmed primarily after the 1970s, though not in an abrupt manner. The fact that the AMIP simulations yield a similar behavior suggests some cause-effect link to the oceans. On the other hand, the CMIP simulations generate a steadier rate of North American warming during the reanalysis period, punctuated by brief pauses due to volcanic aerosol-induced cooling events.

3.4.4.3 Abruptness due to unforced chaotic behavior since 1950

Some rapid climate transitions in recent decades appear attributable to chaotic natural fluctuations. One focus of studies has been the consequence of an apparent shift in the character of ENSO events after the 1970s, with more frequent El Niño warming in recent decades (Trenberth and Hoar, 1996).

Abrupt decreases in rainfall occurred over the southwest United States and Mexico in the 1950s and 1960s (Narisma *et al.*, 2007), with a period of enhanced La Niña conditions during that decade being a likely cause (Schubert *et al.*, 2004; Seager *et al.*, 2005). Nonetheless, this dry period, and the decadal period of the Dust Bowl that preceded it over the Great Plains, did not constitute permanent declines in those region's rainfall, despite meeting some criteria for detecting abrupt rainfall changes (Narisma *et al.*, 2007). In part, the ocean conditions that contributed to these droughts did not persist in their cold La Niña state.

An apparent rapid transition of the atmosphere-ocean system over the North Pacific was observed to occur in 1976 to 77. From an oceanographic perspective, changes in ocean heat content and SSTs that happened suddenly over the Pacific basin north of 30°N were caused by atmospheric circulation anomalies (Miller *et al.*, 1994). These consisted of an unusually strong Aleutian Low that developed in the fall season of 1976, a feature that recurred during many successive winters for the next decade (Trenberth, 1990). These surface features were linked with a persistent positive phase of the PNA teleconnection pattern in the free atmosphere as revealed by reanalysis data. The time series of wintertime Alaskan surface temperatures (Figure 3.19) reveals the mild conditions that suddenly emerged after 1976, and this transition in climate was accompanied by significant shifts in marine ecosystems throughout the Pacific basin (Mantua *et al.*, 1997). It is now evident that this Pacific basin-North American event, while perhaps meeting some criteria for a rapid transition, was mostly due to a large scale coupled-ocean atmosphere variation having multidecadal time scale (Latif and Barnett, 1996). It is thus best viewed as a climate "variation" rather than as an abrupt change in the coupled ocean-atmosphere system (Miller *et al.*, 1994). Such multidecadal variations are readily seen in the observed index of the North Pacific SSTs and also the North Atlantic SSTs. Nonetheless, the Alaskan temperature time series also indicates that there has been no return to cooler surface conditions in recent years. While the pace of anthropogenic warming alone during the last half-century has been more gradual that the rapid warming observed over Alaska, the superposition of an internal decadal fluctuation can lend the appearance of an abrupt warming, as Figure 3.19 indicates occurred over western North America in the mid-1970s. It is plausible that the permanency of the shifted surface warmth is rendered by the progressive increase in the strength of the external anthropogenic signal relative to the amplitude of internal decadal variability.

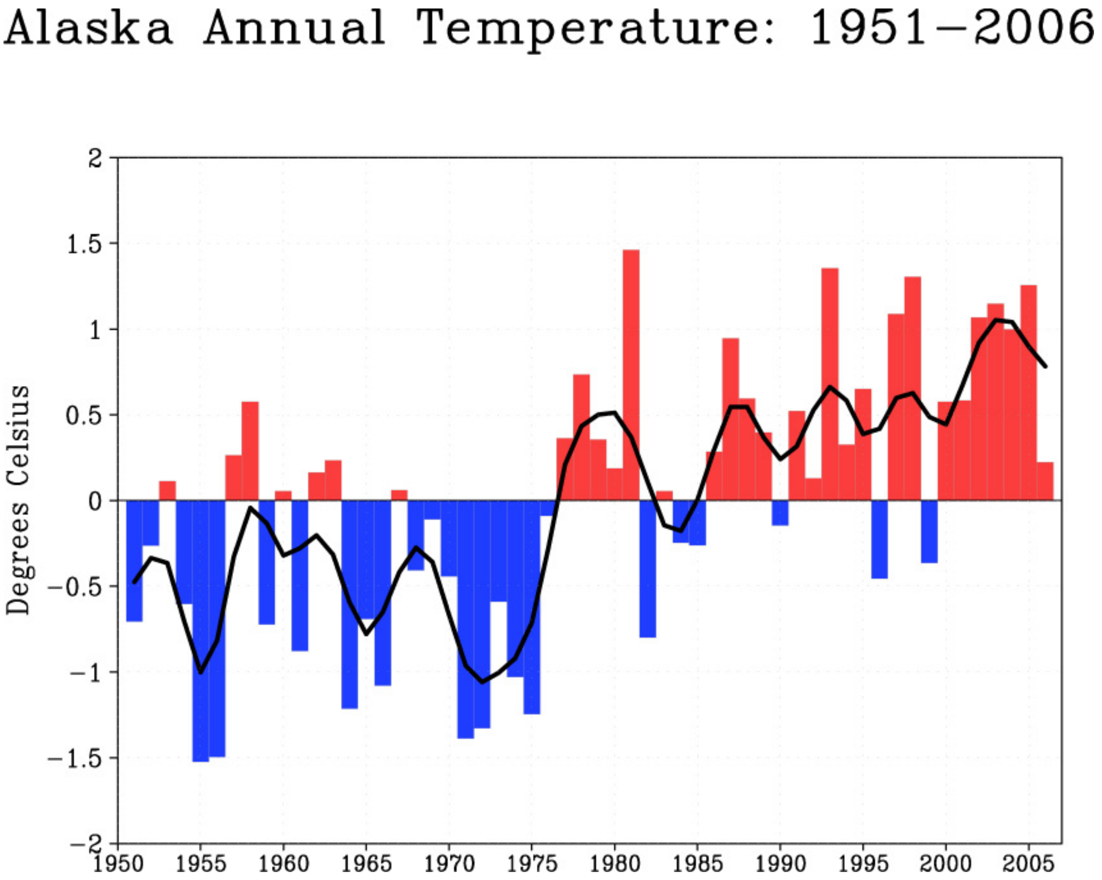

Figure 3.19 Observed Alaska annual surface temperature departures for 1951 to 2006. Anomalies are calculated relative to a 1951 to 2006 reference. Smoothed curve is a 5-point Gaussian filter of the annual departures to emphasize multi-annual variations.

3.5 WHAT IS OUR PRESENT UNDERSTANDING OF THE CAUSES FOR HIGH-IMPACT DROUGHT EVENTS OVER NORTH AMERICA OVER THE REANALYSIS RECORD?

3.5.1. Introduction

Climate science has made considerable progress in understanding the processes leading to drought, in large part owing to the emergence of global observing systems. The analysis of the observational data reveal relationships with atmospheric circulation patterns having large scale, and they illustrate linkages with sea surface temperature patterns as remote from North America as the equatorial Pacific and Indian Ocean. Computing infrastructure - only recently available - is permitting first ever quantifications of the sensitivity of North American climate to various forcings, including ocean temperatures and atmospheric chemical composition.

Such progress, together with the recognition that our Nation's economy suffers dearly during severe droughts, has led to the launch of a National Integrated Drought Information System (NIDIS, 2004) whose ultimate purpose is to develop a timely and useful early warning system for drought.

Credible prediction systems are always enhanced when supported by knowledge of the underlying mechanisms and causes for the phenomenon's variability. In this Chapter, we assess current understanding of the origins of North American drought, focusing on events during the period of abundant global observations since about 1950. Assessments of earlier known droughts (such as the Dust Bowl) serve to identify potential cause-effect relationships that may apply to more recent and future North American regional droughts, and this perspective is provided here as well (see Box 3.3 for discussion of the Dust Bowl).

3.5.2 Definition of Drought

Many definitions for drought appear in the literature, each reflecting its own unique social and economic context in which drought information is desired. Here the focus is on meteorological drought, as opposed to the numerous impacts (and measures) that could be used to characterize drought (*e.g.*, the hydrologic drought indicated by low river flow and reservoir storage, or the agricultural drought indicated by low soil moisture and deficient plant yield).

Meteorological drought has been defined as "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area." (Huschke, ed.,1959). The American Meteorological Society's policy statement defines meteorological drought as a departure from a region's normal balance between precipitation and evapotranspiration (AMS, 1997).

The Palmer Drought Severity Index (PDSI) (Palmer, 1965) measures the deficit in moisture supply relative to its demand at the Earth's surface, and is employed in this Chapter to illustrate some of the major temporal variations of drought witnessed over North America. The Palmer Drought Index is also useful when intercomparing historical droughts over different geographical regions (*e.g.*, Karl, 1983; Diaz, 1983), and it has been found to be a useful proxy of soil moisture and streamflow deficits that relate to the drought impacts having decision-making relevance (*e.g.*, Dai *et al.*, 2004).

3.5.3 Drought Causes

3.5.3.1 Drought statistics, mechanisms and processes

The North American continent has experienced numerous periods of drought during the reanalysis period. Figure 3.20 illustrates the time variability of areal coverage of severe drought since 1951, and on average 10% (14%) of the area of the conterminous (western) United States experiences severe drought each year. The average PDSI for the western states during this time period is shown in the bottom panel; while it is very likely dominated by internal variability, the severity of the recent drought compared with others since 1950 is also apparent.

BOX 3.5 Drought Attribution and Use of Reanalysis Data

The indications for drought itself, such as the Palmer Drought severity Index (PDSI) or precipitation, are not derived from reanalysis data, but from the network of surface observations. The strength of reanalysis data lies in its depiction of the primary variables of the free atmospheric circulation and linking them with the variability in the PDSI. As discussed in Chapter 3, the development and maintenance of atmospheric ridges is the prime ingredient for drought conditions, and reanalysis data is useful for understanding the etymology of such events: their relationship to initial atmospheric conditions, potential downstream and upstream linkages, and the circulation response to soil moisture deficits and SST anomalies. Many drought studies compare model simulations of hypothetical causes to observed atmospheric circulation parameters; reanalysis data can help differentiate among the different possible causes by depicting key physical processes by which drought events evolved.

For final attribution, the drought mechanism must be related to either a specific forcing or internal variability. Reanalysis data, available only since about 1950, is of too short a length to provide a firm indication of internal variability. It also does not indicate (or utilize) direct impact of changing climate forcings, such as increased greenhouse gases or varying solar irradiance. The relationship of atmospheric circulation changes to these forcings must be provided by empirical correlation or, better yet, General Circulation Model (GCM) studies where cause and effect can be directly related.

************ END BOX 3.5 *************

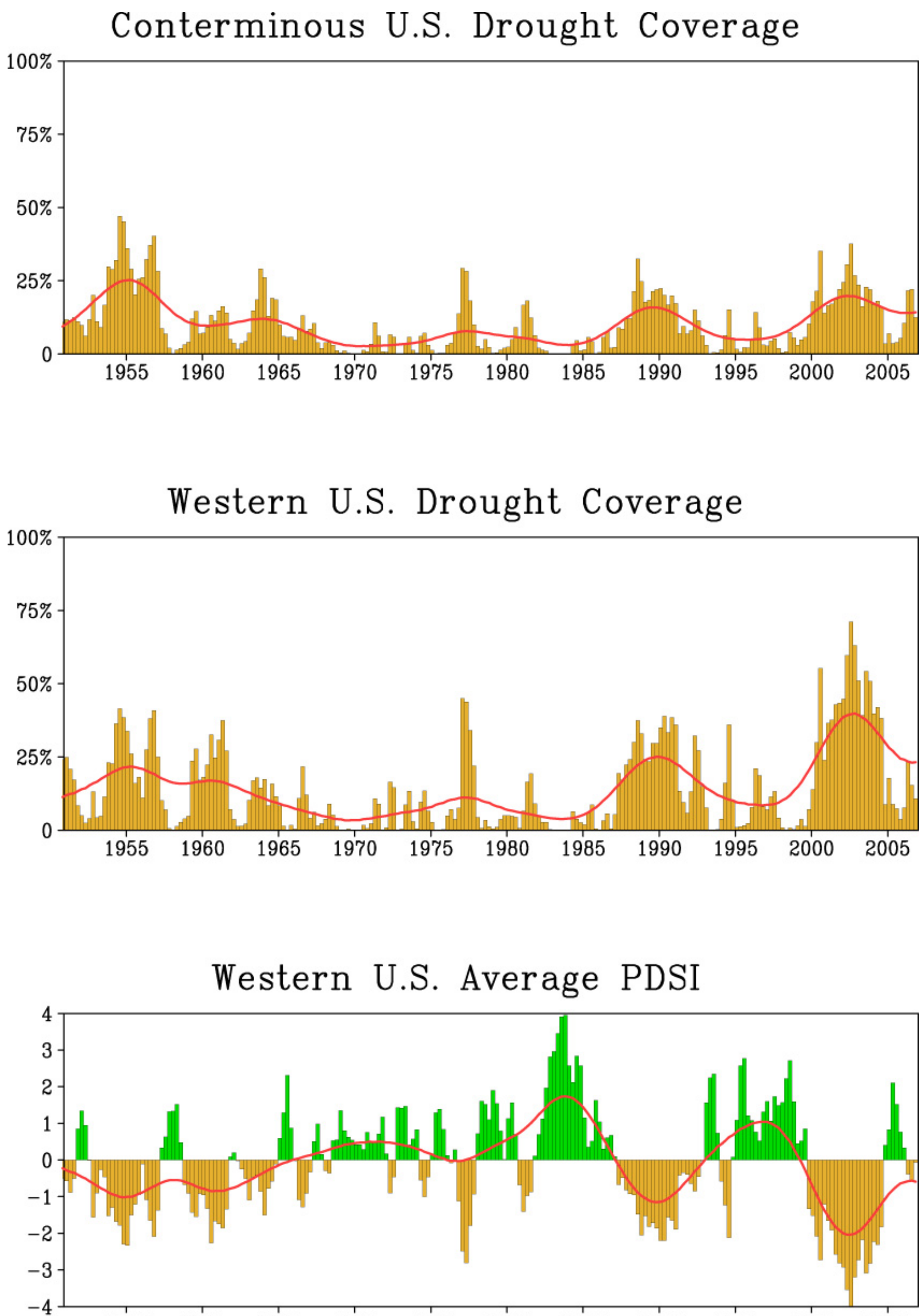

Figure 3.20 Percentage of conterminous United States (top) and western United States (middle) covered by severe or extreme drought, as defined by Palmer Drought Severity Index < -3. Time series of the western United States area averaged PDSI. Positive (Negative) PDSI indicative of above (below) average surface moisture conditions. The Western United States consists of the 11 western-most conterminous U.S. states. Red lines depict time series smoothed with a 9-point Gaussian filter in order to emphasize lower frequency variations.

The middle of the twentieth century began with severe drought that covered much of the United States. Figure 3.21 illustrates the observed surface temperature (top) and precipitation anomalies (bottom) during the early 1950s drought. The superimposed contours are of the 500 mb height from reanalysis data that indicates one of the primary causal mechanisms for drought: high pressure over and upstream that steers moisture-bearing storms away from the drought-affected region.

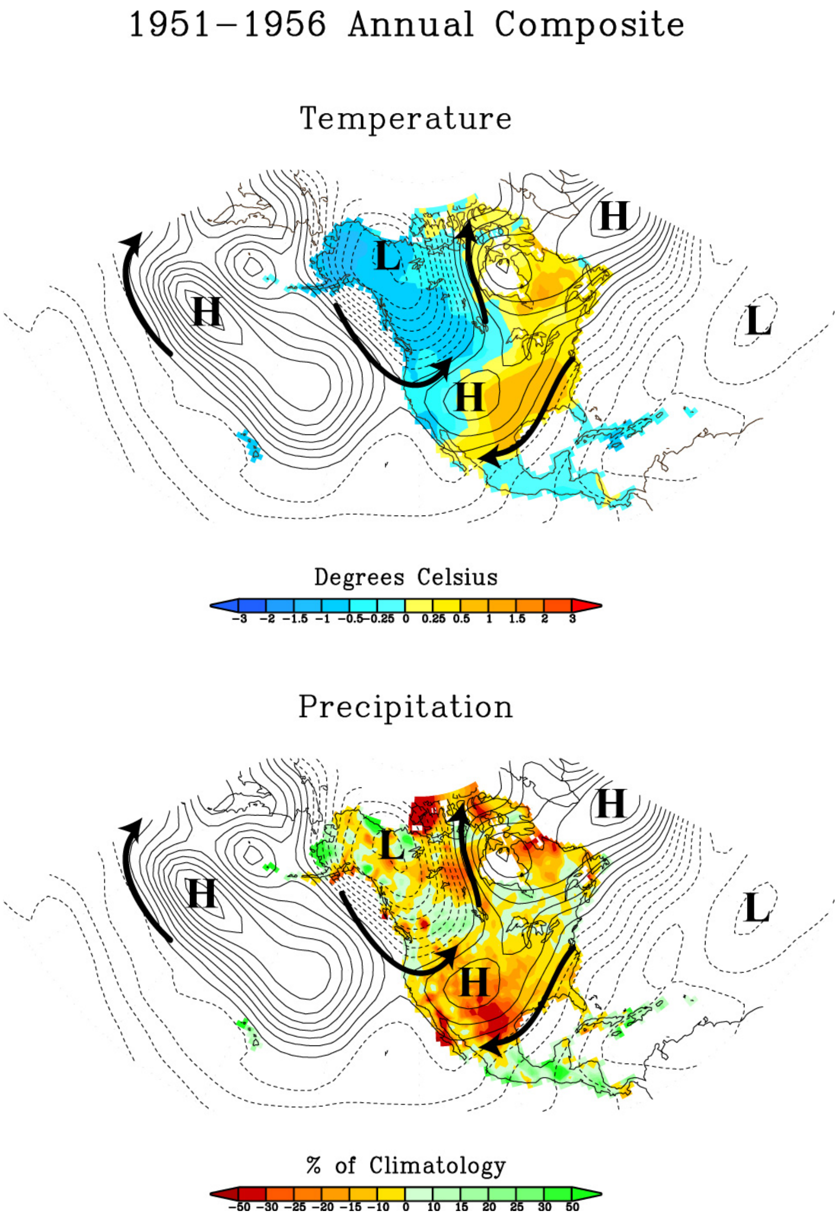

Figure 3.21 Observed climate conditions averaged for 1951 to 1956 during a period of severe Southwest United States drought. The 500mb height field (contours, units 2m) is from the NCEP/NCAR R1 reanalysis. The shading indicates the five-year averaged anomaly of the surface temperature (top) and precipitation (bottom). The surface temperature and precipitation are from independent observational data sets. Anomalous High and Low Pressure regions are highlighted. Arrows indicate the anomalous wind direction, which circulates around the High and Low Pressure centers in a clockwise (counterclockwise) direction.

The northeast United States had severe drought from about 1962 to 1966, with dry conditions extending southwestward into Texas. While the 1970s were relatively free from severe drought, since 1980 there has been an increased frequency of what the National Climatic Data Center (NCDC) refers to as “billion dollar U.S. weather disasters,” many of which are drought events: (1) Summer 1980, central/eastern U.S.;(2) Summer 1986, southeastern U.S.; (3) Summer 1988, central/eastern U.S.; (4) Fall 1995 to Summer 1996, U.S. southern plains; (5) Summer 1998, U.S. southern plains; (6) Summer 1999, eastern U.S.; (7) 2000 to 2002 western U.S./U.S. Great Plains; (8) Spring/summer 2006, centered in Great Plains but widespread.

The droughts discussed above cover various parts of the United States, but in fact droughts are much more common in the central and southern Great Plains. Shown in Figure 3.22 is the mean summer precipitation over the United States (top) and the seasonal standard deviation for the period 1951 to 2006 (bottom). The largest variability occurs along the 95W meridian, while the lowest variability relative to the average precipitation is in the northeast, a distribution that parallels the occurrence of summertime droughts. This picture is somewhat less representative of droughts in the western United States, a region which receives most of its rainfall during winter.

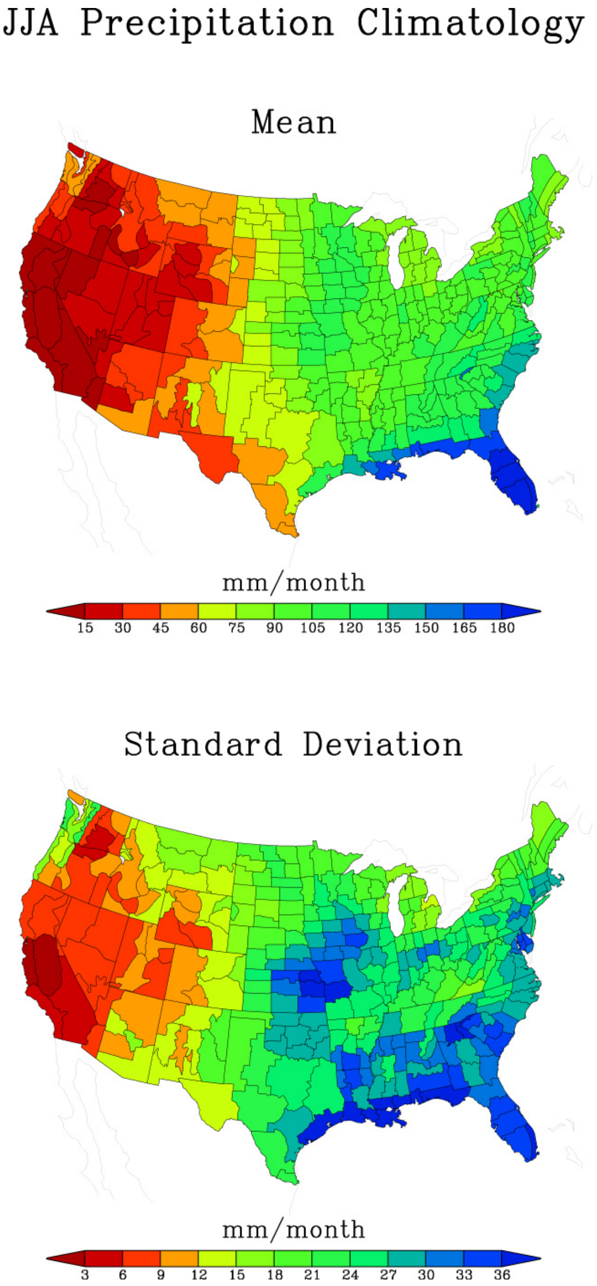

Figure 3.22 Climatological mean (top) and standard deviation (bottom) of summer seasonal mean precipitation over the continental United States for the period 1951 to 2006. Contour intervals are (a) 15 mm month $^{-1}$ and (b) 3 mm day $^{-1}$ (adopted from Ting and Wang, 1997). Data is the NOAA Climate Division data set.

It is natural to ask whether the plethora of recent severe drought conditions identified by NCDC is associated with anthropogenic effects, particularly greenhouse gas emissions. Figure 3.20 shows that the United States area covered by recent droughts (lower panel) is similar to that which prevailed in the 1950s, and is furthermore similar to conditions before the reanalysis period such as the "Dust Bowl" era of the 1930s (Box 3.3). For the western United States (upper panel), paleo-reconstructions of drought conditions indicate that recent droughts are considerably less severe and protracted than those that have been estimated for time periods in the 12th and 13th century from tree ring data (Cook *et al.*, 2004). Hence from a frequency/area standpoint, droughts in the recent decades are not particularly special. To better assess anthropogenic influences on drought, we need to understand the potential causes for these droughts.

While drought can have many definitions, all of the above episodes relate to a specific weather pattern that resulted in reduced rainfall, generally to amounts less than 50% of normal climatological totals. The specific weather pattern in question features an amplified broad-scale high pressure area (ridge) in the troposphere over the affected region (Figure 3.21). Sinking air motion associated with a ridge reduces summertime convective rainfall, results in clear skies with abundant sunshine reaching the surface, and provides for a low level wind flow that generally prevents substantial moisture advection into the region.

The establishment of a stationary wave pattern in the atmosphere is thus essential for generating severe drought. Such stationary, or blocked atmospheric flow patterns can arise due to mechanisms internal to the atmosphere, and the ensuing droughts can be thought of as due to internal atmospheric processes - so-called unforced variability.

However, the longer the anomalous weather conditions persists, the more likely it is to have some stationary forcing acting as a flywheel to maintain the anomalies.

The droughts discussed above can be distinguished by their duration, with longer lasting events more likely involving forcing of the atmosphere. The atmosphere does not have much heat capacity, and its "memory" of past conditions is relatively short (on the order of a few weeks). Hence the forcing required to sustain a situation over seasons or years would be expected to lie outside of the atmospheric domain, and an obvious candidate with greater heat capacity (and hence a longer "memory") is the ocean. Therefore, most studies have assessed the ability of particular ocean sea surface temperature patterns to generate the atmospheric wave pattern that would result in tropospheric ridges in the observed locations during drought episodes.

Namias (1983) pointed out that the flow pattern responsible for Great Plains droughts, with a ridge over the central United States, also includes other region of ridging, one in the East Central Pacific and the other in the East Central Atlantic. As described in Chapter 2 and Section 3.1, these teleconnections represent a standing Rossby wave pattern. Using 30 years of data, Namias showed that if the "tropospheric high pressure center in the Central Pacific is strong, there is a good probability of low heights along the West Coast and high heights over the Plains" (Namias, 1983). This further suggests that the cause for the stationary ridge is not (completely) local, and may have its origins in the Pacific.

Droughts in the western United States are also associated with an amplified tropospheric ridge, further west than for Great Plains droughts that in winter displaces storm tracks north of the United States/Canadian border. In winter, the ridge is also associated with an amplified Aleutian Low in the North Pacific, and this has been associated with forcing from the tropical eastern Pacific in conjunction with El Niño events (*e.g.*, Namias, 1978), whose teleconnection and resulting United States climate pattern has been discussed in Section 3.1

Could ENSO also be responsible for warm-season droughts? Trenberth *et al.* (1988) and Trenberth and Branstator (1992) suggested on the basis of observations and a simplified linear model of atmospheric wave propagation that colder sea surface temperatures in the tropical eastern Pacific (equatorward of 10°N), the La Niña phase of ENSO, in conjunction with the displacement of warmer water and the Intertropical Convergence Zone (ITCZ) northward in that same region (15-20°N), led to the amplified ridging over the United States in the spring of 1988. While this was the leading theory at the time, the general opinion now is that most of the short-term summer droughts are more a product of initial atmospheric conditions (Namias, 1991; Lyon and Dole, 1995; Liu *et al.*, 1998; Bates *et al.*, 2001; Hong and Kalnay, 2002) amplified by the soil moisture deficits that arise in response to lack of precipitation (Wolfson *et al.*, 1987; Atlas *et al.*, 1993; Hong and Kalnay, 2002).

For droughts that occur on the longer time-scale, various possibilities have been empirically related to dry conditions over specific regions of the United States and

Canada. Broadly speaking, they are associated with the eastern tropical Pacific (La Niñas in particular); the western Pacific/Indian Ocean; the north Pacific; and (for the eastern United States) the western Atlantic Ocean. Cool conditions in the eastern tropical Pacific have been related to annual United States droughts in various studies (Barlow *et al.*, 2001; Schubert *et al.*, 2004, Seager *et al.*, 2005), although they are more capable of influencing the United States climate in late winter when the atmospheric mean state is more conducive to allowing an extratropical influence (Newman and Sardeshmukh, 1998; Lau *et al.*, 2006). Warm conditions in the western Pacific/Indian Ocean region are capable of instigating drought in the United States year-round (Lau *et al.*, 2006) but especially in spring (Chen and Newman, 1998). Warmer conditions in the north Pacific have been correlated with drought in the Great Plains (Ting and Wang, 1997) and the northeast United States (Barlow *et al.*, 2001) although modeling studies often fail to show a causal influence (Wolfson *et al.*, 1987; Trenberth and Branstator, 1992; Atlas *et al.*, 1993). The North Pacific SST changes appear to be the result of atmospheric forcing, rather than the reverse – so even if they are contributing to drought conditions, they may not be the cause of the initial circulation anomalies. Alexander *et al.* (2002) concluded from GCM experiments that roughly one quarter to one half of the variance of the dominant pattern of low frequency (greater than ten year) variability in the North Pacific sea surface temperatures during winter was itself the result of ENSO, which helped intensify the Aleutian Low and increased surface heat fluxes (promoting cooling).

Sea surface temperature perturbations downstream of North America, in the North Atlantic have occasionally been suggested as influencing some aspects of United States drought. For example, Namias (1983) noted that the wintertime drought in the western United States in 1977, one of the most extensive Far Western droughts in recent history, appeared to be responsive to a downstream deep trough over the eastern United States. Warmer sea surface temperatures in the western North Atlantic have the potential to intensify storms in that region. Conversely, colder sea surface temperatures in summer can help intensify the ridge (*i.e.*, the “Bermuda High”) that exists in that region. Namias (1966) suggested that just such a cold water regime played an integral part in the Northeast United States spring and summer drought of 1962 to 1965, and Schubert *et al.* (2004) also argue for an Atlantic SST effect on the Dust Bowl, while multi-decadal swings between wet and dry periods over the United States as a whole has been statistically linked with Atlantic SST variations of similar time-scale (McCabe *et al.*, 2004; Figure 3.5).

In Mexico, severe droughts during the reanalysis period were noted primarily in the 1950s, and again in the 1990s. This latter time period featured seven consecutive years of drought (1994 to 2000). As in the United States, droughts in Mexico have been linked to tropospheric ridges that can affect northern Mexico, and also to ENSO. However, there exist additional factors tied to Mexico’s complex terrain and its strong seasonal monsoon rains. Mexican rainfall in the warm season is associated with the North American Monsoon System (NAMS) driven by solar heating, from mid-May into July. Deficient warm season rainfall over much of the country is typically associated with El Niño events. La Niña conditions often produce increased rainfall in southern and northeastern Mexico, but have been associated with drought in northwestern Mexico (Higgins *et al.*, 1999). During winter and early spring, there is a clear association with the ENSO cycle (*e.g.*, Stahle *et al.*, 1998), with enhanced precipitation during El Niño events, associated with a strengthened subtropical jet that steers storms to lower latitudes, and reduced rainfall with La Niñas when the jet moves poleward.

Therefore the occurrence of drought in Mexico is heavily dependent on the state of the ENSO cycle, or its teleconnection to the extratropics, and on solar heating variations. In the warm season there is often an out-of-phase relationship between southern and northern Mexico, and between spring and summer, dependent on the phasing of the NAMS (Therrell *et al.*, 2002). These aspects make attribution of recent droughts difficult. For example, the consecutive drought years from 1994 to 2000 occurred over several different phases of ENSO, suggesting multiple causes including El Niño conditions for warm season drought through 1998, the possible influence of Western Pacific/Indian Ocean warming during the subsequent La Niña phase, and internal atmospheric variability.

Because a large proportion of the variance of drought conditions over North America is unrelated to sea surface temeprature perturbations, it is conceivable that when a severe drought occurs, it is because numerous mechanisms are acting in tandem. This was the conclusion reached in association with the recent United States drought (1999 to 2005) that affected large areas of the southern, western and central United States. During this time, warm conditions prevailed over the Indian Ocean/Western Pacific region along with La Nina conditions in the eastern tropical Pacific – influences from both regions working together may have helped intensify/prolong the annual droughts (Hoerling and Kumar, 2003; Lau *et al.*, 2006).

3.5.3.2 Anthropogenic influences on North American drought since 1951

To the extent that ENSO cycle variations, in particular La Niñas, are the cause of drought in the United States it would be hard to make the case that they are related to greenhouse gas forcing. While it is true that some studies (Clement *et al.*, 1996) have suggested that La Niña conditions will be favored as climate warms, in fact more intense El Niño events have occurred since the late 1970s, perhaps due at least in part to anthropogenic warming of the eastern equatorial Pacific (Mendelssohn *et al.*, 2005). There is a tendency in model projections for the future greenhouse-gas warmed climate to indicate a mean shift towards more El Niño-like conditions in the tropical east Pacific Ocean including the overlying atmospheric circulation; this latter aspect may already be occurring (Vecchi and Soden, 2007). With respect to anthropogenic influence on ENSO variability, Merryfield (2006) surveyed 15 coupled atmosphere-ocean models and found that for future projections, almost half exhibited no change, five showed reduced variability, and three increased variability. Hence to the extent that La Niña conditions are associated with United States drought there is no indication that they have been or will obviously be influenced by anthropogenic forcing.

However, given that SST changes in the Western Pacific/Indian Ocean are a factor for long-term United States drought, a somewhat different story emerges. Shown in Figure 3.23 are the SST anomalies in this region, as well as the tropical central-eastern Pacific

(Lau *et al.*, 2006). As noted with respect to the recent droughts, the Western Pacific/Indian Ocean region has been consistently warm when compared with the 1971 to 2000 sea surface temperature climatology. What has caused this recent warming?

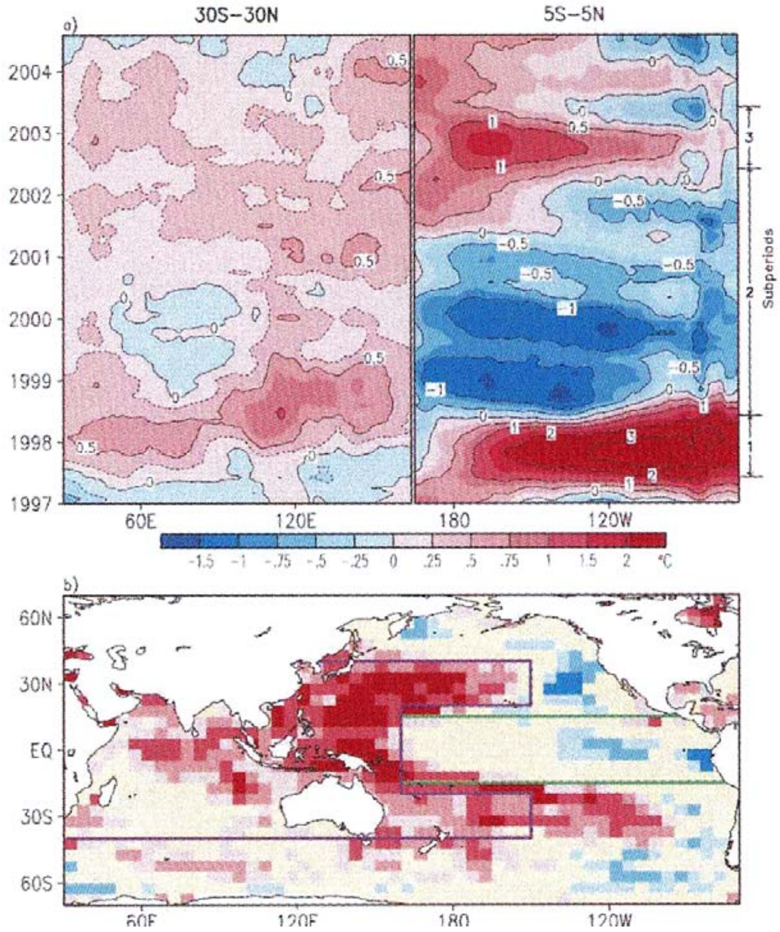

Figure 3.23 Top panel: Sea surface temperature anomalies relative to the period 1970 through 2000 as a function of year in the Indian Ocean/West Pacific (left) and Central-Eastern Pacific (right) (from Lau *et al.*, 2006). Bottom panel: Number of 12-month periods in June 1997-May 2003 with SST anomalies at individual 5° (lat) / 5° (lon) rectangles being above normal (red shading) or below normal (blue shading) by more than one-half of a standard deviation (0.5).

To be sure, more frequent El Niños would by themselves result in increased temperatures in the Indian Ocean, acting through an atmospheric bridge that alters the wind and perhaps cloud field in the Indian Ocean (Klein *et al.*, 1999; Yu and Rienecker, 1999; Alexander *et al.*, 2002; Lau and Nath, 2003); an oceanic bridge between the Pacific and

Indian Ocean has also been modeled ((Bracco *et al.*, 2007). (This effect could then influence droughts over the United States in the summer after an El Nino, as opposed to the direct influence of La Nina [Lau *et al.*, 2005]).

Nevertheless, as shown in Figure 3.23, the warming in the West Pacific/Indian Ocean region has occurred over different phases of the ENSO cycle, making it less likely that the overall effect is associated with it. Hoerling and Kumar (2003) note that "the warmth of the tropical Indian Ocean and the west Pacific Ocean was unsurpassed during the 20th century"; the region has warmed about 1°C since 1950. That is within the range of warming projected by models due to anthropogenic forcing for this region and is outside the range expected from natural variability, at least as judged by coupled atmosphere-ocean model output of the CMIP simulations. (Hegerl *et al.*, 2007, Chapter 9; see in particular Figure 9.12). The comparison of the observed warm pool SST time series with those of the CMIP simulations in previous sections of Chapter 3 indicates that it is very likely that the recent warming of SSTs over the Western Pacific/Indian Ocean region is of anthropogenic origins.

The possible poleward expansion of the subtropical region of descent of the Hadley Circulation is an outcome that is favored by models in response to a warming climate (IPCC, 2007a). It would in effect transfer the dry conditions of northern Mexico to the United States Southwest and southern Great Plains; Seager *et al.* (2007) suggest that may already be happening associated with drought in the southwestern United States.

Additional observations and modeling improvements will be required to assess with greater confidence the likelihood of its occurrence.

An additional impact of greenhouse warming is a likely increase in evapotranspiration during drought episodes because of warmer land surface temperatures. It was noted in the discussion of potential causes that reduced soil moisture from precipitation deficits helped sustain and amplify drought conditions, as the surface radiation imbalance increased with less cloud cover, and sensible heat fluxes increased in lieu of latent heat fluxes. This effect would not have *initiated* drought conditions but would be an additional factor, and one that is likely to grow as climate warms. For example, drier conditions have been noted in the northeast United States despite increased annual precipitation, due to a century-long warming (Groisman *et al.*, 2004), and this appears to be true for Alaska and southern and western Canada as well (Dai *et al.*, 2004). Droughts in the western United States also appear to have been influenced by increasing temperature (Andreadis and Lettenmaier, 2006; Easterling *et al.*, 2007). The area of forest fires in Canada has been high since 1980 compared with the previous 30 years and Alaska experienced record high years in 2004 and 2005 (Soja *et al.*, 2007). Hence global warming by adding additional water stress can exacerbate naturally occurring droughts, in addition to influencing the meteorological conditions responsible for drought.

A further suggestion of the increasing role played by warm surface temperatures on drought is given in Figure 3.24. Shown is a diagnosis of conditions during the recent Southwest United States drought, with contours depicting the atmospheric circulation pattern based on reanalysis data, and shading illustrating the surface temperature anomaly (top) and precipitation anomaly (bottom). High pressure conditions prevailed across the entire continent during the period, acting to redirect storms far away from the region. Continental-scale warmth during 1999 to 2004 was also consistent with the anthropogenic signal. It is plausible that the regional maximum in warmth seen over the Southwest during this period was in part a feedback from the persistently below normal precipitation, together with the anthropogenic signal. Overall, the warmth associated with this recent drought has been greater than that observed during the 1950s drought in the Southwest (Figure 3.21), likely augmenting its negative impacts on water resource and ecologic systems compared to its predecessor

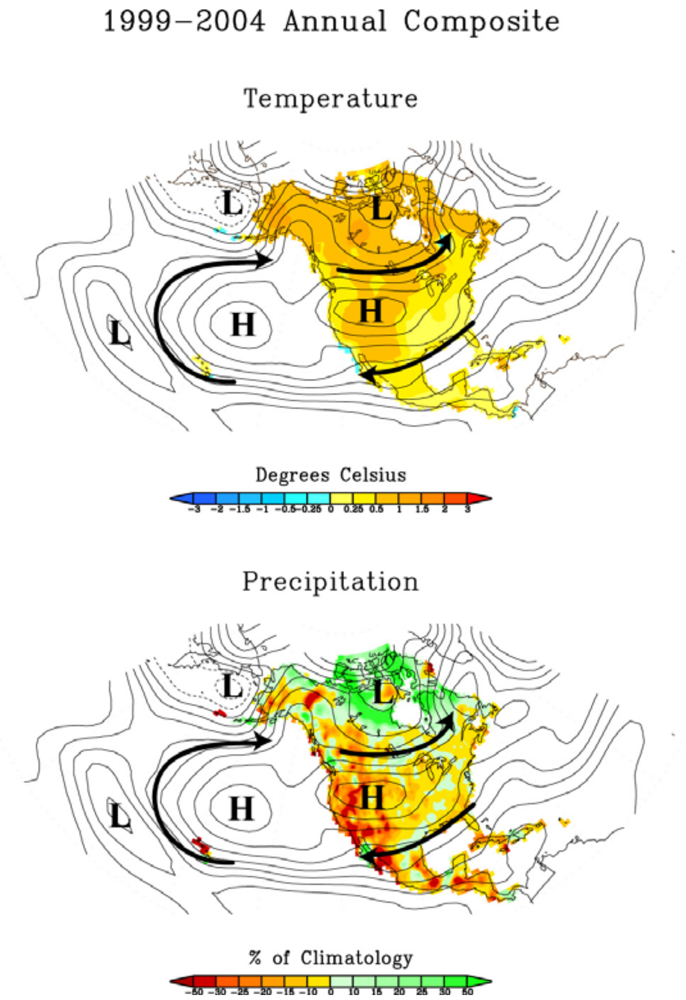

Figure 3.24 Observed climate conditions averaged for 1999 to 2004 during a period of severe southwest United States drought. The 500mb height field (contours, units 2m) is from the NCEP/NCAR R1 reanalysis. The shading indicates the 5-year averaged anomaly of the surface temperature (top) and precipitation (bottom). The surface temperature and precipitation are from independent observational data sets. Anomalous High and Low Pressure regions are highlighted. Arrows indicate the anomalous wind direction, which circulates around the High and Low Pressure centers in a clockwise (counterclockwise) direction.

Breshears *et al.* (2005) estimated the vegetation die-off extent across southwestern North America during the recent drought. The combination of drought with pine bark beetle infestation resulted in >90% loss in Piñon pine trees in some areas. They noted that such a response was much more severe than during the 1950s drought, arguing that the recent drought's greater warmth was the material factor explaining this difference.

Our current understanding is far from complete concerning the origin of individual droughts, both on the short- and long-time scale. While the assessment as discussed here has emphasized the apparently random nature of short-term droughts, a product of initial conditions which then sometimes develop rapidly into strong tropospheric ridges, the exact relationship of such phenomena to sea surface temperature patterns, including the ENSO cycle, is still being debated. The ability of North Atlantic sea surface temperature anomalies to influence the upstream circulation still needs further examination in certain circumstances, especially with respect to droughts in the eastern United States The exact mechanisms for influencing Rossby wave development downstream, including the role of transients relative to stationary wave patterns, will undoubtedly be the subject of continued research. The Hadley Cell response to climate change, as noted above, is still uncertain. And while some modeling studies have emphasized the role played by surface soil moisture deficits in exacerbating these droughts, the magnitude of the effect is somewhat model-dependent, and future generations of land-vegetation models may act somewhat differently.

Given these uncertainties, we conclude from the above analysis that of the severe droughts that have impacted North America over the past five decades, the short term (monthly-seasonal) events are most likely to be primarily the result of initial atmospheric conditions, subsequently amplified by local soil moisture conditions, and in some cases initiated by teleconnection patterns driven in part by SST anomalies. For the longer-term events, the effect of steady forcing through sea surface temperature anomalies becomes more important. Also, the accumulating greenhouse gases and global warming have increasingly been felt as a causative factor, primarily through their influence on Indian Ocean/West Pacific temperatures, conditions to which North American climate is sensitive. The severity of both short- and long-term droughts has *likely* been amplified by local greenhouse gas warming in recent decades.

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Appendix 3.A

Data and Methods Used for Attribution

3.A.1 OBSERVATIONAL DATA

North American surface temperatures during the assessment period of 1951 to 2006 are derived from four data sources. These are the U.K. Hadley Centre's HadCRUT3v (Brohan *et al.*, 2006), NOAA's land/ocean merged data (Smith and Reynolds, 2005), NOAA's global land gridded data (Peterson *et al.*, 1998), and NASA's gridded data (Hansen *et al.*, 2001). For analysis of United States surface temperatures, two additional data sets used are NOAA's U.S. Climate Division data (NCDC, 1994) and the PRISM data (Daley *et al.*, 2002).

Spatial maps of the surface temperature trends shown in Chapter 3 are based on combining all the above data sets. For example, the North American and United States surface temperature trends during 1951 to 2006 were computed for each data set, and the trend map is based on equal-weighted averages of the individual trends. The uncertainity in observations is displayed by plotting the extreme range among the time series of the 1951 to 2006 trends from individual data sets.

North American precipitation data are derived from the Global Precipitation Climatology Project (GPCC) (Rudolf *et al.*, 2005); also consulted is the NOAA gridded precipitation data (Chen *et al.*, 2002), however the North American analysis shown in Chapter 3 is based on the GPCC data alone which is judged to be superior owing to its greater volume of input stations over Canada and Alaska in particular. For analysis of United States precipitaton, two additonal data sets used are NOAA's U.S. Climate Division data and PRISM data. Spatial maps of United States precipitation trends during 1951 to 2006 were computed for each of these three data sets, and the United States trend map is based on equal-weighted averages of the individual trends.

Free atmospheric conditions during 1951 to 2006, including 500 hPa geopotential heights, are derived from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). A comparison of various reanalysis data is provided in Chapter 2, but only the NCEP/NCAR version is available for the entire 1951 to 2006 assessment period.

3.A.2 CLIMATE MODEL SIMULATION DATA

Two configurations of climate models are used in this SAP; atmospheric general circulation models (AMIP), and coupled ocean-atmosphere general circulation models (CMIP). For the former, the data from two different atmospheric models are studied; the European Center/Hamburg model (ECHAM4.5) (Roeckner *et al.*, 1996) whose simulations were performed by the International Research Institute for Climate and Society at LaMont Doherty (L. Goddard, personal communication), and the NASA Seasonal-to-Interannual Prediction Project (NSIPP) model (Schubert *et al.*, 2004) whose simulations were conducted at NASA/Goddard. The models were subjected to specified monthly varying observed global sea surface temperatures during 1951 to 2006. In a procedure that is commonly used in climate science, multiple realizations of the 1951 to

2006 period were conducted with each model in which the separate runs started from different atmospheric initial conditions but were subjected to identically evolving SST conditions. A total of 33 AMIP runs (24 ECHAM and 9 NASA) were available.

The coupled models are those used in the IPCC Fourth Assessment. These are forced with estimated greenhouse gases, aerosols, solar irradiance and the radiative effects of volcanic activity for 1951 to 1999, and with the IPCC Special Emissions Scenario (SRES) A1B (IPCC, 2007) for 2000 to 2006. The model data are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archive as part of the Coupled Model Intercomparison Project (CMIP3). Table 3.1 lists the 19 different models used and the number of realizations conducted with each model. A total of 41 runs were available.

The SST-forced (externally-forced) signal of North American and United States surface temperature and precipitation variability during 1951 to 2006 is estimated by averaging the total of 33 AMIP (41 CMIP) simulations. Trends during 1951 to 2006 were computed for each model run in a manner identical to the observational method; the trend map shown in Chapter 3 is based on an equal-weighted ensemble average of the individual trends. The uncertainty in these simulated trends is displayed graphically by plotting the 5%-95% range amongst the individual model runs.

All the observational and model data used in this SAP are available in the public domain. Further, these data have been widely used for a variety of climate analysis studies as reported in the refereed scientific literature. Table 3.2 provides URLs for each of these data sets.

3.A.3 DATA ANALYSIS AND ASSESSMENT

Analysis of observational and model data is based on standard statistical procedures used extensively in climate research and the physical sciences (von Storch and Zwiers, 1999). Trends for 1951 to 2006 are computed using a linear methodology based on least-squares. Statistical estimates of the significance of the observed trends are based on a non-parametric test in which the 56-year trends are ranked against those computed from CMIP simulations subjected to only natural forcing (solar irradiance and volcanic aerosol). The principal uncertainty in such an analysis is knowing the population of 56-year trends that are expected in the absence of anthropogenic forcing. This Section uses four different coupled models, and a total of sixteen 100-year simulations to estimate the statistical population of naturally occurring 56-year trends, though the existence of model biases is taken into account in making expert assessments.

Observed and model data are compared using routine linear statistical methods. Time series are intercompared using standard temporal correlations. Spatial maps of observed and simulated trends over North America are compared using standard spatial correlation and congruence calculations. Similar empirical methods have been applied for pattern analysis of climate change signals in the published literature (Santer *et al.*, 1994).

Chapter 3 employs expert judgment in arriving at probabilistic attribution statements. The analyses described above are only a small part of the information available to the authors, who also make extensive use of the scientific peer-reviewed literature. For more details on the use of expert assessment in this SAP, the reader is referred to Box 3.4 and the Preface.

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.

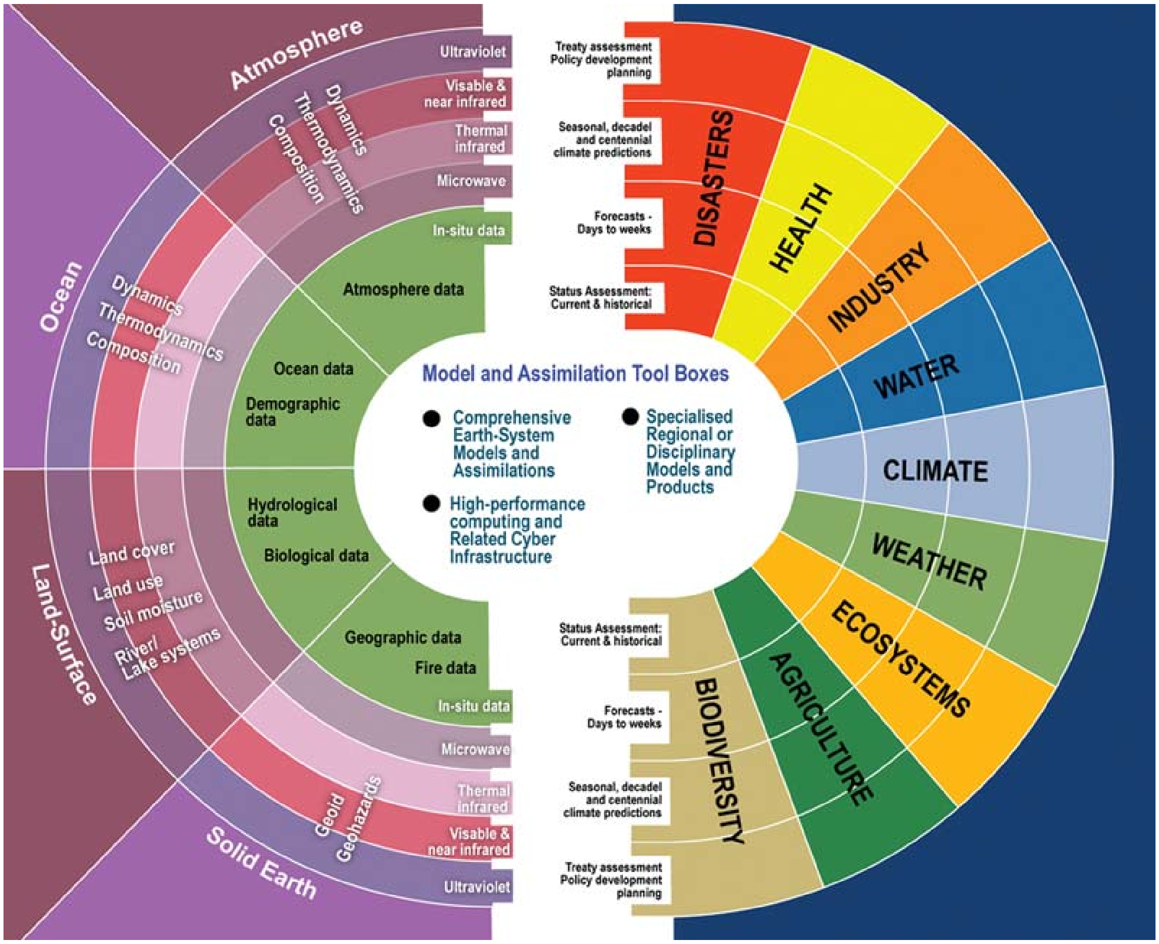

Figure 4.1 From Hollingsworth (2005), based on the GEOSS Implementation Plan (GEOSS, 2005), illustrating the transformation of observations into predictive and current-status information. On the right-hand side are deliverables from an earth system forecasting system and associated specialized models 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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Glossary and Acronyms

GLOSSARY

This glossary defines some specific terms for the context of this report. Most terms below are adapted directly from definitions provided in the IPCC AR4 Glossary (IPCC 2007). Those terms not included in the IPCC report or whose definitions are not identical to the usage in the IPCC Glossary are marked with an asterisk.

Abrupt climate change
The non-linearity of the climate system may lead to abrupt climate change, sometimes called *rapid climate change*, *abrupt events* or even *surprises*. The term "abrupt" often refers to changes that occur on time scales faster than the typical time scale of the responsible forcing. However, abrupt climate changes need not be externally forced, and rapid transitions can result simply from physical or dynamical processes internal to the climate system.

Aerosols
A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 micrometers (μm) and residing in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin.

Analysis*
A detailed representation of the state of the atmosphere and, more generally, other components of the climate system, such as oceans or land surface, that is based on observations.

Annular modes
Preferred patterns of change in atmospheric circulation corresponding to changes in the zonally averaged midlatitude westerlies. The Northern Annular Mode has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation. The Southern Annular Mode occurs in the Southern hemisphere.

Anthropogenic
Resulting from or produced by human beings.

Attribution*
The process of establishing the most likely causes for a detected climate variation or change with some defined level of confidence.

Climate
The statistical description in terms of the mean and variability of relevant atmospheric variables over a period of time ranging from months out to decades, centuries, and beyond. Climate conditions are often described in terms of surface variables such as temperature, precipitation, and wind. Climate in a wider sense is a description of the full

climate system, including, the atmosphere, oceans, cryosphere, the land surface, and biosphere, including their interactions.

Climate change

A change in the state of the climate that can be identified (*e.g.*, using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and changes in land cover and land use.

Climate variability

Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, *etc*.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (*internal variability*), or to variations in natural or anthropogenic external forcing (*external variability*).

Confidence

The likelihood of the correctness of a result as expressed in this report, using a standard terminology defined in the preface.

Data assimilation*

The combining of diverse observations, possibly sampled at different times and intervals and different locations, into a unified and consistent description of a physical system, such as the state of the atmosphere. This combination is obtained by integrating the observations together in a numerical prediction model that provides an initial estimate of the state of the system, or “first guess”.

Drought

In general terms, drought is a “prolonged absence or marked deficiency of precipitation”, a “deficiency that results in water shortage for some activity or for some group,” or a “period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance” (Heim, 2002). Drought has been defined in a number of ways. *Agricultural drought* relates to moisture deficits in the topmost meter or so of soil (the root zone) that impacts crops, *meteorological drought* is mainly a prolonged deficit of precipitation, and *hydrologic drought* is related to below normal streamflow, lake and groundwater levels.

A *megadrought* is a long-drawn out and pervasive drought, lasting much longer than normal, usually a decade or more.

El Niño-Southern Oscillation (ENSO)

El Niño, in its original sense, is a warm water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific east of the dateline. This oceanic event is associated with a fluctuation of a global scale tropical and subtropical surface pressure pattern, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of two to about seven years, is collectively known as El Niño-Southern Oscillation, or ENSO. ENSO is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections with fluctuations elsewhere. The cold phase of ENSO is called *La Niña*.

Ensemble

A group of parallel model simulations. Typical ensemble sizes in many studies range from 10 to 100 members, although this number is often considerably smaller for long runs with the most complex climate models. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include effects of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modeling uncertainty than is possible with traditional multi-model ensembles.

Evapotranspiration

The combined process of evaporation from the Earth's surface and transpiration from vegetation.

Fingerprint

The climate response pattern in space and/or time to a specific forcing. Fingerprints are used to detect the presence of this response in observations and are typically estimated using forced climate model simulations.

Geostrophic wind (or current)

A wind or current that represents a balance between the horizontal pressure gradient and the Coriolis force. The geostrophic wind or current flows directly parallel to isobars with a speed inversely proportional to the spacing of the isobaric contours (*i.e.*, tighter spacing implies stronger geostrophic winds). This is one example of an important balance relationship between two fundamental fields, mass (represented by pressure) and momentum (represented by winds), and implies that information about one of those two fields also implies information on the other.

Land use and **Land-use change**

Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term "land use" is also used in the sense of the social and economic purposes for which land is managed (*e.g.*, grazing, timber extraction, and conservation).

Land-use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus have a radiative forcing and/or other impacts on climate, locally or globally.

Likelihood

The probability of an occurrence, an outcome or a result. This is expressed in this report using a standard terminology, as defined in the preface.

Modes of climate variability

Natural variability of the climate system, in particular on seasonal and longer timescales, predominantly occurs with preferred spatial patterns and timescales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called *regimes* or *modes* or Pacific North American pattern (PNA), the El Niño-Southern Oscillation (ENSO), the Northern Annular Mode (NAM; previously called Arctic Oscillation, AO) and the Southern Annular Mode (SAM; previously called Antarctic Oscillation, AAO). Many of the prominent modes of climate variability are discussed in chapter 2.

Non-linearity

A process where there is no simple proportional relation between cause and effect. The climate system contains many such non-linear processes, resulting in a system with a potentially very complex behavior. Such complexity may lead to abrupt climate change.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation is defined by opposing variations of barometric pressure near Iceland and near the Azores. Through the geostrophic wind relationship, it also corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus also influences storm tracks that influence these regions.

Northern Annular Mode (NAM)

A winter-time fluctuation in the amplitude of a pattern characterized by low surface pressure in the Arctic and strong middle latitude westerlies. The NAM has links with the northern polar vortex into the stratosphere. Its pattern has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation.

Numerical prediction model*

A model that predicts the evolution of the atmosphere (and more generally, other components of the climate system, such as the ocean) through numerical methods that represent the governing physical and dynamical equations for the system. Such approaches are fundamental to almost all dynamical weather prediction schemes, since the complexity of the governing equations do not allow exact solutions.

Pacific Decadal Variability
Coupled decadal-to-interdecadal variability of the atmospheric circulation and underlying ocean in the Pacific basin. It is most prominent in the North Pacific, where fluctuations in the strength of the wintertime Aleutian Low pressure system co-vary with North Pacific sea surface temperature, and are linked to decadal variations in atmospheric circulation, sea surface temperature and ocean circulation throughout the whole Pacific Basin.

Pacific North American (PNA) pattern
An atmospheric large-scale wave pattern featuring a sequence of tropospheric high and low pressure anomalies stretching from the subtropical west Pacific to the east coast of North America.

Paleoclimate
Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

Parameterization
The technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes), by relationships between model-resolved larger scale flow and the area or time averaged effect of such sub-grid scale processes.

Patterns of climate variability
Natural variability of the climate system, in particular on seasonal and longer time-scales, predominantly occurs with preferred spatial patterns and timescales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called regimes, modes or teleconnections. Examples are the North Atlantic Oscillation (NAO), the Pacific-North American pattern (PNA), the El Niño-Southern Oscillation (ENSO), and the Northern and Southern Annual Mode (NAM and SAM). Many of the prominent modes of climate variability are discussed in chapter 2.

Predictability
The extent to which future states of a system may be predicted based on knowledge of current and past states of the system.

Probability Density Function (PDF)
A probability density function is a function that indicates the relative chances of occurrence of different outcomes of a variable.

Reanalysis*
An objective, quantitative method for representing past weather and climate conditions and, more generally, conditions of other components of the Earth's climate system such as the oceans or land surface. An important goal of most reanalysis efforts to date has been to reconstruct a detailed, accurate, and continuous record of past global atmospheric conditions, typically at time intervals of every six to 12 hours, over periods of decades or longer. This reconstruction is accomplished by integrating observations obtained from numerous data sources together within a numerical prediction model through a process called data assimilation.

Sea-surface temperature
The bulk temperature in the top few meters of the ocean. Measurements are made by ships, buoys and drifters.

Storm tracks
Originally a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the regions where the main tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems.

Stratosphere
The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km altitude.

Teleconnection
A connection between climate variations over widely separated parts of the world. In physical terms, teleconnections are often a consequence of large-scale wave motions, whereby energy is dispersed from source regions along preferred paths in the atmosphere.

Troposphere
The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and weather phenomena occur. In the troposphere temperatures generally decrease with height.

ACRONYMS

AGCM	Atmospheric General Circulation Model
AMIP	Atmospheric Model Intercomparison Project
AMO	Atlantic Multi-decadal Oscillation
AMS	American Meteorological Society
AR4	IPCC Fourth Assessment Report
BC	black carbon
CCCma-CGCM3.1(T47)	a Canadian Centre for Climate Modelling and Analysis model
CCSM3	a National Center for Atmospheric Research model
CCSP	Climate Change Science Program
CFS	Climate Forecast System
CFSRR	Climate Forecast System Reanalysis and Reforecast Project
CMIP	Coupled Model Intercomparison Project
CNRM-CM3	a Météo-France/Centre National de Recherches Météorologiques model
CRU	Climate Research Unit
CRUTEM	Climate Research Unit Land Temperature Record
CSIRO	Commonwealth Scientific and Industrial Organization
CSIRO-Mk3.0	a CSIRO Marine and Atmospheric Research model
CTD	Conductivity Temperature Depth
DJF	December-January-February
DOE	Department of Energy
ECHAM5/MPI-OM	a Max-Planck Institute for Meteorology model
ECMWF	European Center for Medium-Range Weather Forecasting
ENSO	El Niño-Southern Oscillation
ESMF	Earth System Modeling Framework
EU	European Union
FAR	fraction of attributable risk
FGGE	First GARP Global Experiment
FGOALS-g1.0	an Institute for Atmospheric Physics model
GARP	GEMPAK Analysis and Rendering Program
GCHN	Global Historical Climatology Network
GCM	Global Circulation Model
GCOS	Global Climate Observing System
GEMPAK	General Meteorology Package
GEMS	Global Environment Monitoring System
GEOS	Goddard Earth Observing System
GEOSS	Global Earth Observing System of Systems
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL-CM2.0	a Geophysical Fluid Dynamics Laboratory model
GFDL-CM2.1	a Geophysical Fluid Dynamics Laboratory model
GISS	Goddard Institute for Space Studies
GISS-EH	a Goddard Institute for Space Studies model
GISS-ER	a Goddard Institute for Space Studies model
GMAO	Global Modeling and Assimilation Office
GODAR	Global Oceanographic Data Archaeology and Rescue
GPCC	Global Precipitation Climatology Project
GRIPS	GCM-Reality Intercomparison Project for SPARC
GSI	grid-point statistical interpolation
HIRS	High-resolution Infrared Radiation Sounder

ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IDAG	International Ad Hoc Detection and Attribution Group
IESA	integrated Earth system analysis
INM-CM3.0	an Institute for Numerical Mathematics model
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM4	Institute Pierre Simon Laplace model
ITCZ	Intertropical Convergence Zone
JAMSTEC	Frontier Research Center for Global Change in Japan
JJA	June-July-August
LDAS	Land Data Assimilation System
LLJ	low-level jet
MERRA	Modern Era Retrospective-Analysis for Research and Applications
MIROC3.2(medres)	a Center for Climate System Research model
MIROC3.2(hires)	a Center for Climate System Research model
MJO	Madden-Julian Oscillation
MRI	Meteorological Research Institute
MRI-CGCM2.3.2	a Meteorological Research Institute model
MSU	Microwave Sounding Unit
NAM	Northern Annular Mode
NAMS	North American Monsoon System
NAO	North Atlantic Oscillation
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NIDIS	National Integrated Drought Information System
NIES	National Institute for Environmental Studies
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSIPP	NASA Seasonal-to-Interannual Prediction Project
OSE	Observing System Experiments
PCM	National Center for Atmospheric Research model
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PIRATA	Pilot Research Moored Array in the Atlantic
PNA	Pacific North American Pattern
PRISM	Precipitation-elevation Regressions on Independent Slopes Model
QBO	Quasi-Biennial Oscillation
SAP	Synthesis and Assessment Product
SNOTEL	Snowpack Telemetry
SODA	Simple Ocean Data Assimilation
SPARC	Stratospheric Processes and their Role in Climate
SRES	(IPCC) Special Emissions Scenario
SST	sea surface temperature
SSU	Stratospheric Sounding Unit
TAO	Tropical Atmosphere Ocean
TAR	IPCC Third Assessment Report
T2M	two meter height temperature
UKMO-HadCM3	a Hadley Centre for Climate Prediction and Research model

UKMO-HadGEM1	a Hadley Centre for Climate Prediction and Research model
WCRP	World Climate Research Programme
WOAP	WCRP Observations and Assimilation Panel
WOD	World Ocean Database
XBT	expendable bathythermograph