CHAPTER 1

Introduction

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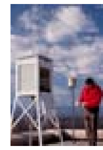


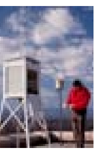
FUNDAMENTAL CONCEPTS

Among the most frequent questions that the public and decision makers ask climate scientists are: What do we know about past climate? What are the uncertainties in observations of climate? What do we know about the causes of climate variations and change? What are the uncertainties in explaining the causes for observed climate conditions? The scientific methods of climate *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 remainder of the Product.

1.1 REANALYSIS

In atmospheric science, an *analysis* is a detailed representation of the state of the atmosphere that is based on observations (Geer, 1996). More generally, an analysis may also be performed for other parts of the climate system, such as the oceans or land surface. The analysis is often displayed as a map depicting the values of a single variable such as air temperature, wind speed, or precipitation amount, or of multiple variables for a specific time period, level, and region. 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 1.1a). Analyses are also performed at levels above the Earth's surface (Figure 1.1b) in order to provide a complete depiction of atmospheric conditions throughout the depth of the atmosphere. This type of analysis enables atmospheric scientists to locate key atmospheric features, such as the jet stream, and plays a crucial role in weather forecasting by providing initial conditions required for models used for weather prediction.

A retrospective analysis, or *reanalysis*, is an objective, quantitative method for producing a high quality sequence of analyses that extends over a sufficiently long time period to have value for climate applications (as well as for other purposes). An important goal of most reanalysis efforts to date has been to provide an accurate and consistent long-term data record of the global atmosphere. As discussed in Chapter 2, reanalyses have also been conducted or are in progress for the oceans and land surface. In certain cases, a reanalysis may be performed for a single variable, such as precipitation or surface temperature (Fuchs, 2007). However, in many modern atmospheric reanalyses the goal is to develop an accurate and physically consistent representation of an extensive set of variables (*e.g.*, winds, temperatures, pressures, *etc.*) required to provide a comprehensive, detailed depiction of how the atmosphere has evolved over an extended period of time (typically, decades). Such comprehensive reanalyses are a major focus of this assessment.



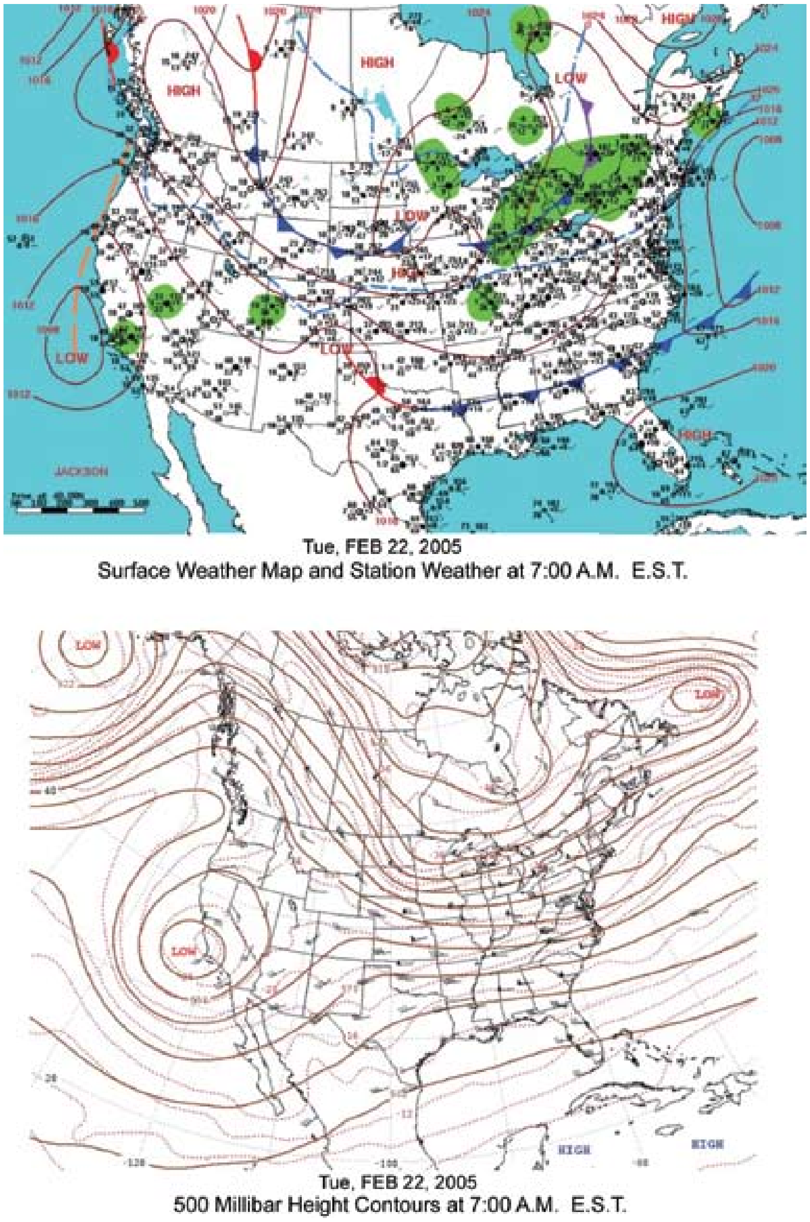


Figure 1.1 Examples of map analyses for a given day (February 22, 2005) for the continental United States and adjacent regions. (a) Surface weather analysis, or "weather map". Contours are lines of constant pressure (isobars), while green shaded areas denote precipitation. Positions of low pressure and high pressure centers, fronts and a subset of surface station locations providing observations that underpin the analysis are also shown. (b) A map of the heights (solid lines, in decameters) and temperatures (dotted lines, in °C) of a constant pressure surface, in this case the 500 millibar surface, which represents conditions at an elevation of approximately 18,000 feet. 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 open end depicting the observation station location (*e.g.*, winds over Denver, Colorado on this day are from the west, while those over Oakland, California are from the east). Note the strong relationship between the wind direction and the height contours, with the station winds blowing nearly parallel to the height contour lines shown in the analysis (and counter-clockwise around lows, as for example the low center just off the California coast). This is an example of a balanced relationship that is used to help construct the analyses, as discussed in Chapter 2.

The reanalysis efforts assessed in this Product estimate past conditions using a method that integrates observations from numerous data sources (Figure 1.2) together within a state-of-the art atmospheric model (or a model of another climate system component, such as the ocean or land surface). This data-model integration provides a comprehensive, high quality, temporally continuous, and physically consistent dataset of atmospheric variables for use in climate research and applications. The models provide physical consistency by constraining the analysis to be consistent with the fundamental laws that govern relationships among the different variables. Details on these methods are described in Chapter 2.

The atmospheric reanalyses assessed in the Product provide values for all atmospheric variables over the entire globe, extending in height from the Earth's surface up to elevations of approximately 30 miles. These values provide a continuous, detailed record of how the atmosphere has evolved every 6 to 12 hours over periods spanning multiple decades. Henceforth, in this Product the term *reanalysis* refers to this specific method for reconstructing past weather and climate conditions, unless stated otherwise.

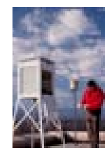
Chapter 2 describes reanalysis methods and assesses the strengths and limitations of current reanalysis products, including representations of seasonal-to-decadal climate variations and regional trends in surface temperatures and precipitation. Specific questions addressed in that Chapter are:

- What is a climate reanalysis? What role does reanalysis play within a comprehensive climate observing system?
- What can reanalysis tell us about climate processes and their representation in models used for climate predictions and climate change projections?
- 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; that is, from data that are not included in constructing the reanalysis?

- What steps would be most useful in reducing false jumps and trends in climate time series (those that may be due to changes in observing systems or other non-physical causes) and other uncertainties in past climate conditions through improved reanalysis methods? Specifically, what contributions could be made through advances in data recovery or quality control, modeling, and/or data assimilation techniques?

Figure 1.2 An illustration of some diverse types of observational systems that provide data used to construct a weather or climate analysis. 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 also provide data that is combined to produce a comprehensive climate system analysis.



The assessment of capabilities and limitations of current reanalysis datasets for various purposes will be of value for determining best uses of current reanalysis products for scientific and practical purposes. This Chapter will also be useful for science program managers in developing priorities for improving the scientific and practical value of future climate reanalyses.

1.2 ATTRIBUTION

The term *attribute* has as a common use definition "to assign to a cause or source" (Webster's II Dictionary, 1988). The Intergovernmental Panel on Climate Change (IPCC) has 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, 2007a). The term attribution in this Product is used in the same context as the IPCC definition. However, here the scope is broadened to include observed climate variations as well as detected climate change. There are three primary reasons for expanding the scope to include climate variations: (1) climate variations often have large economic impacts on regions and communities in the United States, sometimes in the billions of dollars (NCDC, 2007); (2) there is strong public interest in explanations of the causes of major short-term climate variations, for example, related to the El Niño-Southern Oscillation (ENSO), severe droughts, and other extreme events; and (3) many impacts of climate change are likely to be experienced through changes in extreme weather and climate events; that is, through changes in variability as well as changes in average conditions (IPCC, 2007b).

Methods for attributing the causes of observed climate variations and trends are discussed in Chapter 3, including the use of reanalysis data for this purpose. This Chapter focuses on observed climate variations and changes over the North American region, extending from approximately 1950 to the present, the maximum time extent of current reanalysis records. The key questions are:

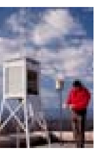
- What is climate attribution? What are the scientific methods used for establishing attribution?
- What is the present understanding of the causes for North American climate trends in annual temperature and precipitation during the reanalysis record?
- What is the present understanding of causes for seasonal and regional variations in U.S. temperature and precipitation trends over the reanalysis record?

The assessment of capabilities and limitations of current reanalysis datasets for various purposes will be of value for determining best uses of current reanalysis products for scientific and practical purposes.

- What are the nature and causes of apparent rapid climate shifts that are relevant to North America over the reanalysis record?
- What is the present understanding of the causes for high-impact drought events over North America during the reanalysis record?

This Chapter will aid policy makers in assessing present scientific understanding and remaining uncertainties regarding the causes of major climate variations and trends over North America since the mid-twentieth century. Resource managers and other decision makers, as well as the general public, will also benefit from this assessment, especially for those events that have high societal, economic, or environmental impacts, such as major droughts.

Reanalysis can be considered as playing a central role in determining *what* has happened in the climate system, while attribution is necessary to address the question of *why* the changes have occurred.



1.3 CONNECTIONS BETWEEN REANALYSIS AND ATTRIBUTION

This Product focuses on two major topics: climate reanalysis and attribution. Are there scientific connections between reanalysis and attribution and, specifically, why might reanalysis be useful for determining attribution? Figure 1.3 illustrates schematically some key steps commonly used in climate science including reanalysis and attribution.

1.3.1 Steps in climate science

Observations provide the foundation for all of climate science. The observations are obtained from numerous disparate observing systems (see Figure 1.2) and are also distributed irregularly both in time and space over the Earth. These issues and others pose significant challenges to scientists in evaluating present climate conditions and in comparing present conditions with those of the past.

As discussed previously, an analysis is a method for combining diverse observations to obtain a quantitative (numerical) depiction of the state of the atmosphere or, more generally, the state of the climate system at a given time (Figure 1.3). Reanalysis corresponds to the step of applying the same analysis method to carefully reconstruct the past climate history. Extending the record back in time enables scientists to detect climate variations and changes, and to compare present and past conditions. This reanalysis must apply consistent methods and quality-controlled data in order to accurately identify changes over time and determine how changes in different variables such as winds, temperatures, and precipitation are related. In climate science, attribution corresponds to what in medical science is called diagnosis; that is, it is the process of identifying the cause or causes of the feature of interest. As in medical science, additional "diagnostic tests" are often required to establish attribution. In climate science, these additional tests most commonly consist of controlled experiments conducted with climate models; results are compared between model outcomes when a climate forcing of interest (*e.g.*, from changes in greenhouse gases or volcanic aerosols) is either included or excluded in order to assess its potential effects.

Establishing attribution provides a scientific underpinning for predicting future climate and information useful for evaluating needs and options for adaptation and/or mitigation due to climate variability or change. Detailed discussions of climate prediction, adaptation, and mitigation are beyond the scope of this

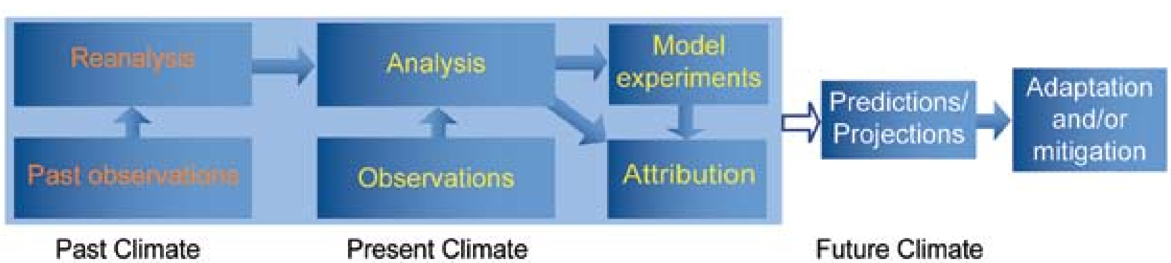


Figure 1.3 Schematic illustrating some key steps in climate science. The shaded box indicates the general scope of this Product. The arrows show the general flow of information leading to decision support for adaptation and/or mitigation. As indicated by the open arrow, the description and understanding of past and current climate conditions included within the shaded box provide key information for developing reliable predictions of future climate and for evaluating options for adaptation and/or mitigation.

Product; however, recognition of such relationships helps illuminate potential applications of, and connections between, climate reanalysis and attribution.

1.3.2 Further comments

Reanalysis can be considered as playing a central role in determining *what* has happened in the climate system (what has changed, and by how much?), while attribution is necessary to address the question of *why* the changes have occurred. As illustrated by Figure 1.3, observations serve as the fundamental starting point for climate reanalysis; observations themselves are generally not sufficient to establish attribution; models incorporating fundamental understanding of key physical processes and their relationships are also required. The event of interest, *e.g.*, a long-term trend or other feature, such as a severe drought, must first be identified with confidence in the data in order for attribution to be meaningful. Reanalysis often plays an important role in this regard by providing a comprehensive, high quality, and continuous climate dataset spanning several decades. Physical consistency, obtained through the use of a model that incorporates the fundamental governing laws of the climate system, is also a primary feature of reanalysis datasets. Physical consistency enables identification of the roles of various processes in producing climate variations and change along with corresponding linked patterns of variability. Thus, the method of reanalysis can contribute to more confident attribution of the processes that produce responses within the climate system to a given climate forcing, as well as the expected geographical patterns and magnitudes of the responses.

One potential application of reanalysis data is in the detection of climate change. Within the IPCC, detection of climate change is defined as 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 cause for the detected change with some level of confidence. Reanalysis can play an important role in both detecting and attributing causes of climate variations and change; however, it is vital to recognize that reanalysis alone is seldom sufficient and that the best methods for both detection and attribution often depend on results obtained from a broad range of datasets, models, and analysis techniques.

In order to establish more definitive attribution, climate scientists perform controlled climate model experiments to determine whether estimated responses to particular climate forcings are consistent with the observed climate features of interest (*e.g.*, a sustained temperature trend or a drought). Reanalysis data can also be of considerable value in evaluating how well climate models represent observed climate features and responses to different forcings over several decades, thereby providing important guidance of the utility of the models for establishing attribution.

There are inevitable uncertainties associated with observational data, analysis techniques, and climate models. Therefore, climate change detection and attribution findings must be stated in probabilistic terms based on current knowledge, and expert judgment is often required to assess the evidence regarding particular processes (see Chapter 3). The language on uncertainty adopted in this Product is consistent with the IPCC Fourth Assessment Report (IPCC, 2007a). Finally, it is important to recognize that in complex systems, whether physical, biological, or human, it is often not one factor but the interaction among multiple factors that determines the ultimate outcome.

1.4 REANALYSIS APPLICATIONS AND USES

Over the past several years, reanalysis datasets have become a cornerstone for research in advancing our understanding of how and why climate has varied since the mid-twentieth century. For example, Kalnay *et al.* (1996), the initial overview paper on one of the first reanalysis datasets produced in the United States, has been cited more than 5500 times in the peer-reviewed literature as of mid-2008 and is currently the most widely cited paper in the geophysical sciences (ISI Web of Knowledge, <http://www.isiwebofknowledge.com/>; see also Figure 1.4).

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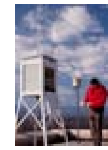


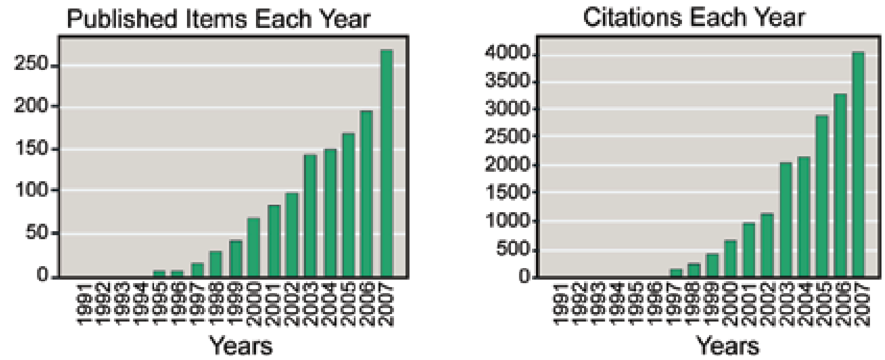
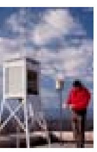


Figure 1.4 The number of published items and citations from an "ISI Web of Science" search with the key words REANALYSIS and CLIMATE.

Increasingly, reanalysis data are being used in a wide range of practical applications. One important application is to address the question: "How is the present climate similar to, or different from, past conditions?" The short time intervals of reanalysis data (typically, every 6 to 12 hours) enable detailed studies of the time evolution of specific weather and climate events as well as comparisons with similar events in the past, providing important clues on key physical processes. Intercomparisons of different reanalyses and observational datasets help to provide a measure of the uncertainty in representations of past climate, including identifying phenomena, regions, and time periods for which confidence in features is relatively high or low (Santer *et al.*, 2005).



Reanalysis datasets are increasingly used for practical applications in sectors such as energy, agriculture, water resources, and insurance.

Reanalysis datasets are also increasingly used for practical applications in sectors such as energy, agriculture, water resources, and insurance (*e.g.*, Schwartz and George, 1998; Pryor *et al.*, 2006; Challinor *et al.*, 2005; Pulwarty, 2003; Pinto *et al.*, 2007). For example, a recently completed high-resolution regional reanalysis, the North American Regional Reanalysis (Mesinger *et al.*, 2006), focuses on improving the representation of the water cycle over North America in order to better serve water resource management needs. Chapter 2 of this Product will inform users of strengths and limitations of current reanalysis datasets, and aid in determining whether certain datasets are suited for specific purposes. Chapter 3 will be of value to policy-makers and the public in providing an assessment of current scientific understanding on the causes for observed climate variations and change over North America from the mid-twentieth century to the present. Finally, Chapter 4 recommends steps needed to improve national capabilities in reanalysis and attribution in order to increase their value for scientific and practical applications.