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).

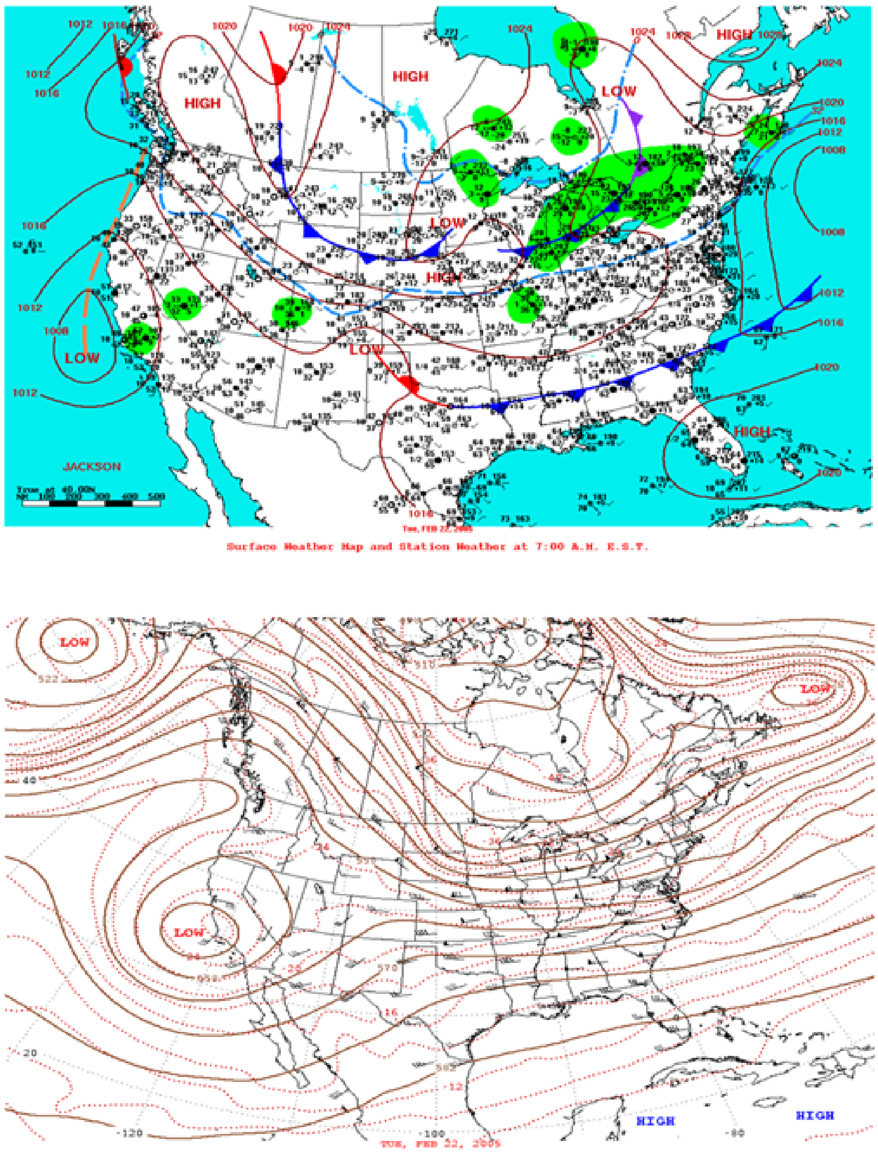

Figure 1.1 Examples of map analyses for a given day (February 22, 2005) for the continental United States and adjacent regions. *Top figure:* surface weather analysis, or "weather map". Contours are lines of constant pressure (isobars), while green shaded areas denote precipitation. Positions of low 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.

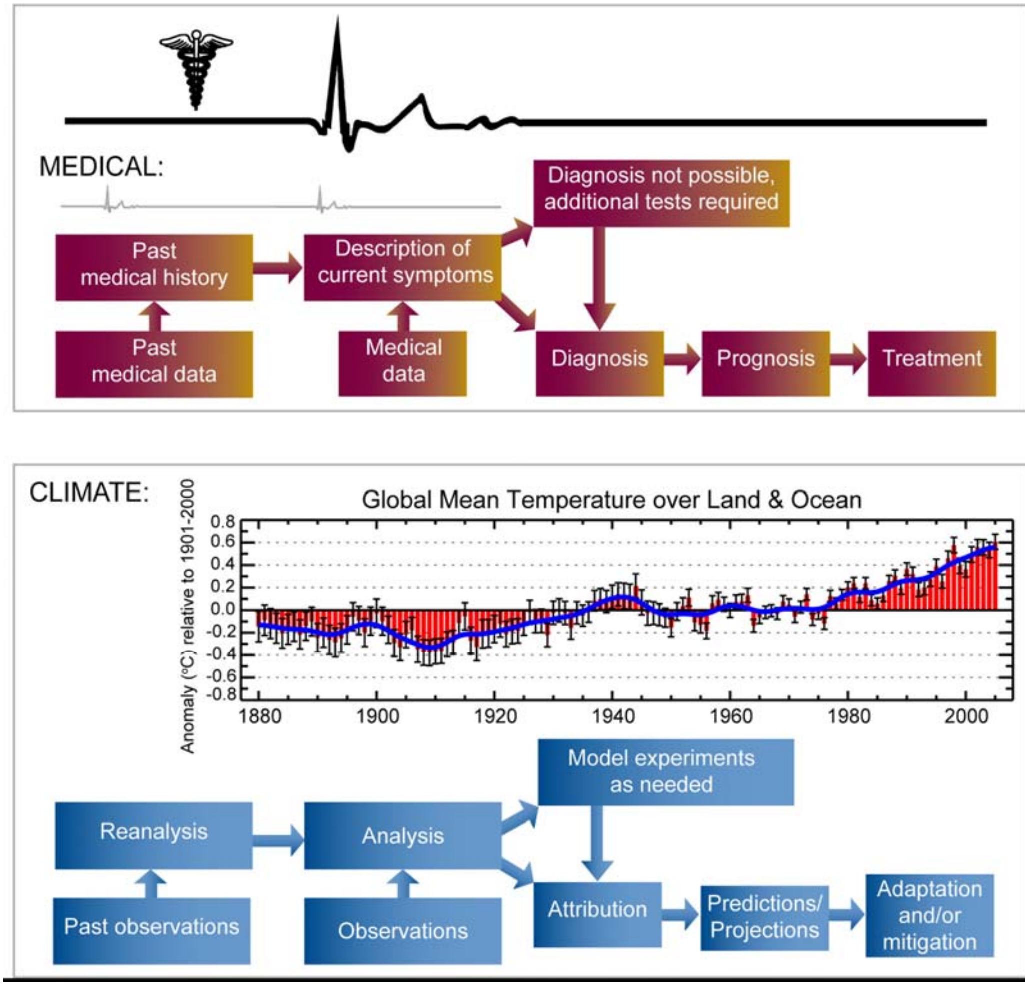

Figure 1.3 Schematic illustrating the analogy between approaches used in medicine and climate science, as discussed in the text.

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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