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.