CHAPTER 4

Measures To Improve Our Understanding of Weather and Climate Extremes

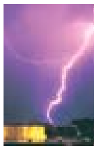
Convening Lead Author: David R. Easterling, NOAA

Lead Authors: David M. Anderson, NOAA; Stewart J.Cohen,Environment Canada and University of British Columbia; William J. Gutowski, Jr., Iowa State Univ.; Greg J. Holland, NCAR; Kenneth E. Kunkel, Univ. Ill. Urbana-Champaign, Ill. State Water Survey; Thomas C. Peterson, NOAA; Roger S. Pulwarty, NOAA; Ronald J. Stouffer, NOAA; Michael F. Wehner, Lawrence Berkeley National Laboratory

BACKGROUND

In this chapter we identify areas of research and activities that can improve our understanding of weather and climate extremes. Many of these research areas and activities are consistent with previous reports, especially the CCSP SAP 1.1 report, *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences,* on reconciling temperature trends between the surface and free atmosphere.

Many types of extremes, such as excessively hot and cold days, drought, and heavy precipitation show changes over North America consistent with observed warming of the climate. Regarding future changes, model projections show large changes in warm and cold days consistent with projected warming of the climate by the end of the 21st century. However, there remains uncertainty in both observed changes, due to the quality and homogeneity of the observations, and in model projection, due to constraints in model formulation, in a number of other types of climate extremes, including tropical cyclones, extratropical cyclones, tornadoes, and thunderstorms.



4.1

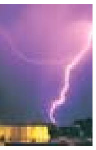
The continued development and maintenance of high quality climate observing systems will improve our ability to monitor and detect future changes in climate extremes.

Recently, more emphasis has been placed on the development of true climate observing networks that adhere to the Global Climate Observing System (GCOS) Climate Monitoring Principles. This is exemplified by the establishment in the United States of the Climate Reference Network, in Canada of the Reference Climate Network, and recent efforts in Mexico to establish a climate observing network. Stations in these networks are carefully sited and instrumented and are designed to be benchmark observing systems adequate to detect the true climate signal for the region being monitored.

Similar efforts to establish a high-quality, global upper-air reference network have been undertaken under the auspices of GCOS. However, this GCOS Reference Upper-Air Network (GRUAN) is dependent on the use of current and proposed new observing

stations, whose locations will be determined through observing system simulation experiments (OSSEs) that use both climate model simulations and observations to determine where best to locate new observing stations.

However, at the present these efforts generally are restricted to a few countries and large areas of the world, even large parts of North America remain under observed. Developing climate observing networks, especially in areas that traditionally have not had long-term climate observations, would improve our ability to monitor and detect future changes in climate, including extremes.



4.2

Efforts to digitize, homogenize, and analyze long-term observations in the instrumental record with multiple independent experts and analyses improve our confidence in detecting past changes in climate extremes.

Research using homogeneity-adjusted observations provides a better understanding of climate system variability in extremes. Observations of past climate have, by necessity, relied on observations from weather observing networks established for producing and verifying weather forecasts. In order to make use of these datasets in climate analyses, non-climatic changes in the data, such as changes due to station relocations, land-use change, instrument changes, and observing practices must be accounted for through data adjustment schemes. The intent of these data adjustments is to approximate homogeneous time series where the variations are only due to variations in climate and not due to the non-climatic changes discussed above. However, the use of these adjustment schemes introduces another layer of uncertainty into the results of analyses of climate variability and change. Thus, research into both the methods and quantifying uncertainties introduced through use of these methods would improve understanding of observed changes in climate.

Even with the recent efforts to develop true climate observing networks, an understanding of natural and human effects on historical weather and climate extremes is best achieved through study of very long (century-scale) records because of the presence of multidecadal modes of variability in the climate system. For many of the extremes discussed here, including temperature and precipitation extremes, storms, and drought, there are significant challenges in this regard because long-term, high-quality, homogeneous records are not available. For example, recent efforts have been made in the United States to digitize surface climate data for the 19th century; however, using these data poses several problems. The density of stations was also considerably less than in the 20th century. Equipment and observational procedures were quite variable and different than the standards established within the U.S. Cooperative Network (COOP) in the 1890s. Thus, the raw data are not directly comparable to COOP data. However, initial efforts to homogenize these data have been completed and analysis shows interesting features, including high frequencies of extreme precipitation and low frequencies of heat waves for the 1850-1905 period over the conterminous United States.

In some cases, heterogeneous records of great length are available and useful information has been extracted. However, there are many opportunities where additional research may result in longer and higher quality records to better characterize the historical variations. For example, the ongoing uncertainty and debate about tropical cyclone trends is rooted in the heterogeneous nature of the observations and different approaches toward approximating homogeneous time series. Efforts to resolve the existing uncertainties in tropical cyclone frequency and intensity should continue by the re-examination of the heterogeneous records by a variety of experts to insure that multiple perspectives on tropical cyclone frequency are included in critical data sets and analyses. However, this notion of multiple independent experts and analyses should not be restricted to the question of tropical cyclone frequency, but should be applied to all aspects of climate research.

4.3

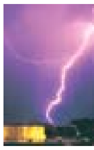
Weather observing systems adhering to standards of observation consistent with the needs of both the climate and the weather research communities improve our ability to detect observed changes in climate extremes.

Smaller-scale storms, such as thunderstorms and tornadoes are particularly difficult to observe since historical observations have been highly dependent on population density. For example, the U.S. record of tornadoes shows a questionable upward trend that appears to be due mainly to increases in population density in tornado-prone regions. With more people in these regions, tornadoes that may have gone unobserved in earlier parts of the record are now being recorded, thus hampering any analysis of true climate trends of these storms. Since many of the observations of extreme events are collected in support of operational weather forecasting, changes in policies and procedures regarding those observations need to take climate change questions into account in order to collect high-quality, consistently collected data over time and space. Therefore, consistent standards of collection of data about tornadoes and severe thunderstorms would be beneficial. Included in this process is a need for the collection of information about reports that allows users to know the confidence levels that can be applied to reports.

However, in the absence of homogeneous observations of extremes, such as thunderstorms and tornadoes, one promising method to infer changes is through the use of surrogate measures. For example, since the data available to study past trends in these kinds of storms suffer from the problems outlined above, an innovative way to study past changes lies in techniques that relate environmental conditions to the occurrence of thunderstorms and tornadoes. Studies along these lines could then produce better relationships than presently exist between favorable environments and storms. Those relationships could then be applied to past historical environmental observations and reanalysis data to make improved estimates of long-term trends.

4.4

Extended recontructions of past climate using weather models initialized with homogenous surface observations would help improve our understanding of strong extratropical cyclones and other aspects of climate variability.

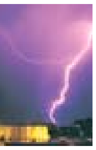


Studies of the temporal variations in the frequency of strong extratropical cyclones have typically examined the past 50 years and had to rely on reanalysis fields due to inconsistencies with the historical record. But a much longer period would enable a better understanding of possible multidecadal variability in strong storms. There are surface pressure observations extending back to the 19th century and, although the spatial density of stations decreases backwards in time, it may be possible to identify strong extratropical cyclones and make some deductions about long-term variations. Additionally, efforts to extend reanalysis products back to the early 20th century using only surface observations have recently begun. These efforts are desirable since they provide physically-consistent depictions of climate behavior and contribute to an understanding of causes of observed changes in climate extremes.

4.5

The creation of annually-resolved, regional-scale reconstructions of the climate for the past 2,000 years would help improve our understanding of very long-term regional climate variability.

The development of a wide-array of climate reconstructions for the last two millennia, such as temperature, precipitation, and drought would provide a longer baseline to analyze infrequent extreme events, such as those occurring once a century or less. This and other paleoclimatic research can also answer the question of how extremes change when the global climate was warmer and colder than today.



The instrumental record of climate is generally limited to the past 150 years or so. Although there are observations of temperature and precipitation as recorded by thermometers and rain gauges for some locations prior to the early to mid-1800s, they are few and contain problems due to inconsistent observing practices, thus their utility is limited. However, the paleoclimate record covering the past 2,000 years and beyond reveals extremes of greater amplitude and longer duration compared to events observed in the instrumental record of the past 100 years (*e.g.*,Woodhouse and Overpeck, 1998). The paleoclimate record also reveals that some events occur so infrequently that they may be observed only once, or even not at all, during the instrumental period. An improved array of paleo time series would improve understanding of the repeat frequency of rare events, for example, events occurring only once a century.

The frequency of some extremes appears tied to the background climate state, according to some paleoclimate records. For example, century-scale changes in the position of the subtropical high may have affected hurricane tracks and the frequency of hurricanes in the Gulf of Mexico (Elsner *et al.*, 2000). Throughout the western United States, the area exposed to drought may have been elevated for four centuries from 900-1300 A.D., according to the Palmer Drought Severity Index reconstructed from tree rings (Cook *et al.*, 2004). The period from 900-1300 A.D. was a period when the global mean temperature was above average (Mann *et al.*, 1999), consistent with the possibility that changes in the background climate state can affect some extremes. The paleoclimatic record can be used to further understand the possible changes in extremes during warmer and colder climates of the past.

4.6

Improvements in our understanding of the mechanisms that govern hurricane intensity would lead to better short- and long-term predictive capabilities.

A major limitation of our current knowledge lies in the understanding of hurricane intensity together with surface wind structure and rainfall, and particularly how these relate to a combination of external forcing from the ocean and surrounding atmosphere, and potentially chaotic internal processes. This lack of understanding and related low predictive capacity has been recognized by several expert committees set up in the wake of the disastrous 2005 Atlantic hurricane season:

The National Science Board recommended that the relevant federal agencies commit to a major hurricane research program to reduce the impacts of hurricanes and encompassing all aspects of the problem: physical sciences, engineering, social, behavioral, economic, and ecological (NSB, 2006);

- The NOAA Science Advisory Board established an expert Hurricane Intensity Research Working Group that recommended specific action on hurricane intensity and rainfall prediction (NOAA SAB, 2006);
- The American Geophysical Union convened a meeting of scientific experts to produce a white paper recommending action across all science-engineering and community levels (AGU, 2006); and
- A group of leading hurricane experts convened several workshops to develop priorities and strategies for addressing the most critical hurricane issues (HiFi, 2006).

While much of the focus for these groups was on the short-range forecasting and impacts reduction aspects of hurricanes, the research recommendations also apply to longer term projections. Understanding the manner in which hurricanes respond to their immediate atmospheric and oceanic environment would improve prediction on all scales.

An issue common to all of these expert findings is the need for understanding and parameterization of the complex interactions occurring at the high-wind oceanic interface and for very high model resolution in order for forecast models to be able to capture the peak intensity and fluctuations in intensity of major hurricanes. Climate models are arriving at the capacity to resolve regional structures but not relevant details of the hurricane core region. As such, some form of statistical inference will be required to fully assess future intensity projections.

4.7

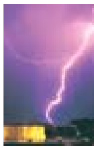
Establishing a globally-consistent wind definition for determining hurricane intensity would allow for more consistent comparisons across the globe.

A major issue with determining the intensity of hurricanes lies with the definition of wind speed. The United States uses a one-minute average and the rest of the world uses ten minutes, which causes public confusion. For example, a hurricane could be reported using one-minute winds while it was still a tropical storm by a ten-minute standard. This is becoming more serious with the spread of global news in which a U.S. television channel can be reporting a hurricane while the local news service is not. A related issue lies with comparing aircraft and numerical model "winds" with those recorded by anemometers: an aircraft is moving through the atmosphere and reports an inherently different wind; the wind speed in a model is dependent on the grid spacing and time step used.

4.8

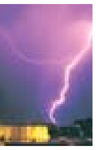
Improvements in the ability of climate models to recreate the recent past as well as make projections under a variety of forcing scenarios are dependent on access to both computational and human resources.

The continued development and improvement of numerical climate models, and observational networks for that matter, is highly related to funding levels of these activities. A key factor is the recruitment and retention of people necessary to perform the analysis of models and observations. For the development and analysis of models, scientists are drawn to institutions with supercomputing resources. For example, the high resolution global simulations of Oouchi *et al.* (2006) to predict future hurricane activity are currently beyond the reach of U.S. tropical cyclone research scientists. This limitation is also true for other smaller-scale storm systems, such as severe thunderstorms and tornadoes. Yet, to understand how these extreme events might change in the future it is critical that climate models are developed that can realistically resolve these types of weather systems. Given sufficient computing resources, current U.S. climate models can achieve very high horizontal resolution. Current generation high performance computing (HPC) platforms are also sufficient, provided that enough access to computational cycles is made available. Furthermore, many other aspects of the climate system relevant to extreme events, such as extra-tropical cyclones, would be much better simulated in such integrations than they



are at current typical global model resolutions.

Even atmospheric models at approximately 20 kilometer horizontal resolution are still not finely resolved enough to simulate the high wind speeds and low pressure centers of the most intense hurricanes (Category 5 on the Saffir-Simpson scale). Realistically capturing details of such intense hurricanes, such as the inner eyewall structure, will require models up to one kilometer horizontal resolution. Such ultra-high resolution global models will require very high computational rates to be viable (Wehner *et al.*, 2008). This is not beyond the reach of next generation HPC platforms but will need significant investments in both model development (human resources) as well as in dedicated computational infrastructure (Randall, 2005).



4.9

More extensive access to high temporal resolution data (daily, hourly) from climate model simulations both of the past and for the future would allow for improved understanding of potential changes in weather and climate extremes.

In order to achieve high levels of statistical confidence in analyses of climate extremes using methods such as those based on generalized extreme value theory, lengthy stationary datasets are required. Although climate model output is well suited to such analysis, the datasets are often unavailable to the research community at large. Many of the models utilized for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) were integrated as ensembles, permitting more robust statistical analysis. The simulations were made available at the Program for Climate Model Diagnostics and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory. However, the higher temporal resolution data necessary to analyze extreme events is quite incomplete in the PCMDI database, with only four models represented in the daily averaged output sections with ensemble sizes greater than three realizations and many models not represented at all. Lastly, a critical component of this work is the development of enhanced data management and delivery capabilities such as those in the NOAA Operational Model Archive and Distribution System (NOMADS), not only for archive and delivery of model simulations, but for reanalysis and observational data sets as well (NRC, 2006).

4.10

Research should focus on the development of a better understanding of the physical processes that produce extremes and how these processes change with climate.

Analyses should include attribution of probability distribution changes to natural or anthropogenic influences, comparison of individual events in contemporary and projected climates, and the synoptic climatology of extremes and its change in projected climates. The ultimate goal should be a deeper understanding of the physical basis for changes in extremes that improves modeling and thus lends confidence in projected changes.

Literature is lacking that analyzes the physical processes producing extremes and their changes as climate changes. One area that is particularly sparse is analysis of so-called “compound extremes,” events that contain more than one type of extreme, such as drought and extremely high temperatures occurring simultaneously.

A substantial body of work has emerged on attribution of changes, with a growing subset dealing with attribution of changes in extremes. Such work shows associations between climate forcing mechanisms and changes in extremes, which is an important first step toward understanding what changes in extremes are attributable to climate change. However, such work typically does not examine the coordinated physical processes linking the extreme behavior to the climate in which it occurs.

More effort should be dedicated to showing how the physical processes producing extremes are changing. Good examples are studies by Meehl and Tebaldi (2004) on severe heat waves, Meehl *et al.* (2004) on changes in frost days, and Meehl and Hu (2006) on megadroughts. Each of these examples involves diagnosing a coherent set of climate-system processes that yield the extreme behavior. An important aspect of the work is demonstrating correspondence between observed and simulated physical processes that yield extremes and, in some of these cases, evaluation of changes in the physical processes in projected climates.

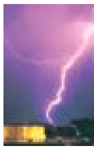
More broadly, the need is for greater analysis of the physical climatology of the climate system leading to extremes. Included in this are further studies of the relationship in projected future climates between slow oscillation modes, such as PDO and AO, and variation in extremes (*e.g.*, Thompson and Wallace, 2001). Methods of synoptic climatology (*e.g.*, Cassano *et al.,* 2006; Lynch *et al.,* 2006) could also provide deeper physical insight into the processes producing extremes and their projected changes. Also, the development and use of environmental proxies for smaller storm systems, such as severe thunderstorms and tornadoes from regional and nested climate models, is encouraged. Finally, more probability analysis of the type applied by Stott *et al.* (2004) to the 2003 European heat wave is needed to determine how much the likelihood of individual extreme events has been altered by human influences on climate.

4.11

Enhanced communication between the climate science community and those who make climate-sensitive decisions would strengthen our understanding of climate extremes and their impacts.

Because extremes can have major impacts on socioeconomic and natural systems, changes in climate extremes (frequency, timing, magnitude) will affect the ability of states, provinces and local communities to cope with rare weather events. The process of adaptation to climate change begins with addressing existing vulnerabilities to current and near-term climatic extremes and is directly linked to disaster risk management. Research and experience have shown that reducing the impacts of extremes and associated complex multiple-stress risks, require improvements in i) early warning systems, ii) information for supporting better land-use planning and resource management, iii) building codes, and iv) coordination of contingency planning for pre- and post-event mitigation and response.

Because the links between impacts and changes in extremes can be complex, unexpected, and highly nonlinear, especially when modified by human interventions over time, research into these linkages should be strengthened to better understand system vulnerabilities and capacity, to develop a portfolio of best practices, and to implement better response options. But best practices guidelines do not do any good unless they are adequately communicated to the relevant people. Therefore, mechanisms for collaboration and exchange of information among climate scientists, impacts researchers, decision makers (including resources managers, insurers, emergency officials, and planners), and the public should be developed and supported. Such mechanisms would involve multi-way information exchange systems and pathways. Better communication between these groups would help communities and individuals make the most appropriate responses to changing extremes. As climate changes, making the complexities of climate risk management explicit



can transform event to event response into a learning process for informed proactive management. In such learning-by-doing approaches, the base of knowledge is enhanced through the accumulation of practical experience for risk scenario development and disaster mitigation and preparedness.

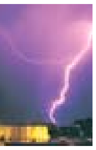
4.12

A reliable database that links weather and climate extremes with their impacts, including damages and costs under changing socioeconomic conditions, would help our understanding of these events.

Many adaptations can be implemented at low cost, but comprehensive estimates of adaptation costs and benefits are currently limited, partly because detailed information is not adequately archived and made available to researchers. To address this problem, guidelines should be developed to improve the methods to collect, archive, and quality control detailed information on impacts of extreme events and sequences of extremes, including costs (of emergency responses), insured and uninsured loss estimates (including property and commercial/business), loss of life, and ecological damage, as well as the effectiveness of post event responses. Additionally, networks of systematic observations of key elements of physical, biological, and socioeconomic systems affected by climate extremes should be developed, particularly in regions where such networks are already known to be deficient.

There are increasing calls for more and improved structured processes to assess climatic risks and communicate such information for economic and environmental benefit (Pulwarty *et al.*, 2007). Fortunately, there are prototypes of such processes and programs from which lessons may be drawn. The NOAA Regional Integrated Sciences and Assessments (RISA) program represents a widely acknowledged, successful effort to increase awareness of climate risks and to foster multi-way risk communication between research and practitioners. RISAs conduct research that addresses critical complex climate sensitive issues of concern to decision makers and policy planners at a regional level. The RISAs are primarily based at universities with some team members based at government research facilities, non-profit organizations, or private sector entities. More recently, state governments, Watershed Commissions and federal agencies are requesting that the information products of programs, such as RISAs and Regional Climate Centers, be coordinated across agencies, states, and tribal nations to inform proactive risk-reduction measures and adaptation practices (Pulwarty *et al.*, 2007).

In the case of drought, the creation of the National Integrated Drought Information System (NIDIS) represents the culmination of many years of experience from scientific inquiry, monitoring insight and socioeconomic impacts. The NIDIS is based on interagency teams and working groups at federal, state, and local levels. This broad experience base and increasingly cross-sectoral vulnerability to extremes points to the need for a unified federal policy to help states and local communities prepare for and mitigate the damaging effects of drought across temporal and spatial scales (NIDIS Act 2006 Public Law 109-430). The NIDIS is a dynamic and accessible drought risk information system. It provides com-



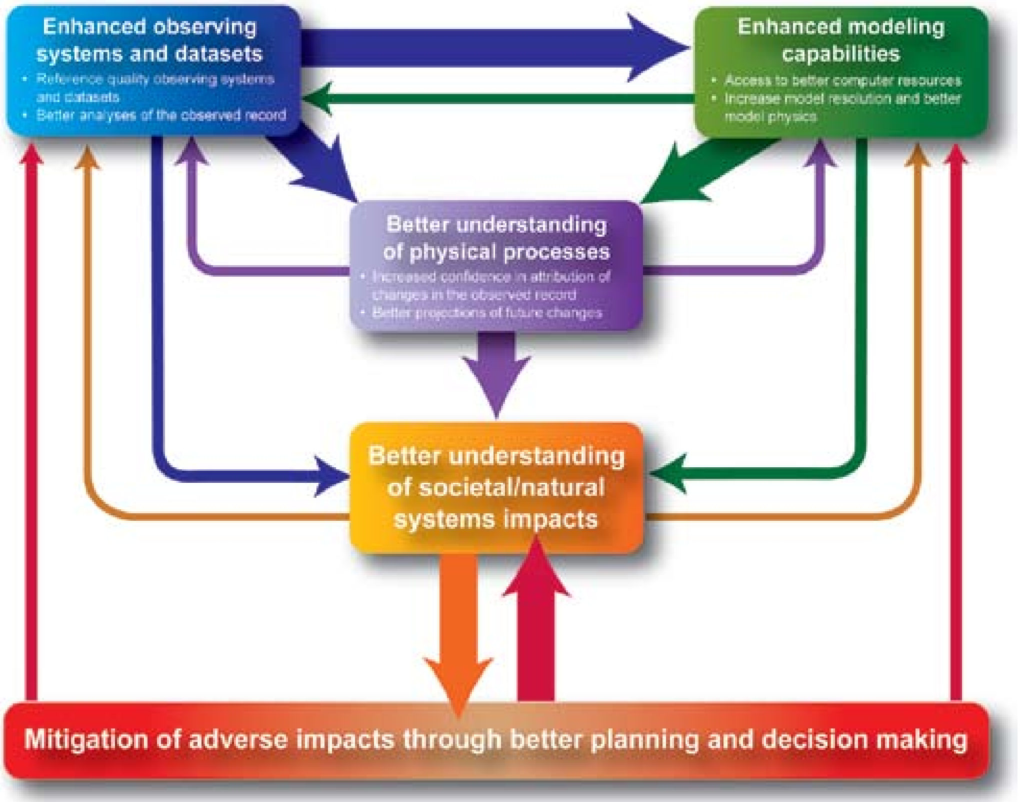
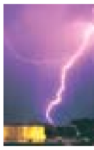


Figure 4.1 Interrelationships between inputs and components leading to better understanding. Thick arrows indicate major linkages included in this assessment. Better observing systems result in improved analyses which helps improve modeling, physical understanding, and impacts through clearer documentation of observed patterns in climate. Similarly, improved modeling helps improve physical understanding and, together, can point to deficiencies in observing systems as well as helping to understand future impacts. Lastly, a better understanding of the relationships between climate extremes and impacts can help improve observations by identifying deficiencies in observations (*e.g.*, under-observed areas), and improve modeling efforts by identifying specific needs from model simulations for use in impacts studies.



munities engaged in drought preparedness with the capacity to determine the potential impacts of drought in their locale, and develop the decision support tools, such as risk management triggers, needed to better prepare for and mitigate the effects of drought. At present, NIDIS focuses on coordinating disparate federal, state, and local drought early warning systems and plans, and on acting as an integrated drought information clearinghouse, scaling up from county to watersheds and across timescales of climate variability and change.

4.13

Summary

Figure 4.1 shows the complex interrelationships between the different sections and recommendations in this chapter. Enhanced observing systems and data sets allow better analyses of the observed climate record for patterns of observed variability and change. This provides information for the climate modeling community to verify that their models produce realistic simulations of the observed record, providing increased confidence in simulations of future climate. Both of these activities help improve our physical understanding of the climate which, linked with model simulations through observing system simulation experiments, helps understand where we need better observations, and leads to better formulation of model physics through process studies of observations. This link between observed and modeling patterns of climate change also provides the basis for establishing the cause and effect relationships critical for attribution of climate change to human activities. Since the ultimate goal of this assessment is to provide better information to policy and decision makers, a better understanding of the relationships between climate extremes and their impacts is critical information for reducing the vulnerability of societal and natural systems to climate extremes.