Weather and Climate Extremes in a Changing Climate

Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands

U.S. Climate Change Science Program
Synthesis and Assessment Product 3.3

June 2008

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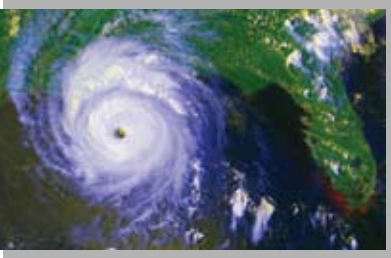
This Synthesis and Assessment Product described in the U.S. Climate Change Science Program (CCSP) Strategic Plan, was prepared in accordance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and the information quality act guidelines issued by the Department of Commerce and NOAA pursuant to Section 515 <http://www.noaanews.noaa.gov/stories/iq.htm>). The CCSP Interagency Committee relies on Department of Commerce and NOAA certifications regarding compliance with Section 515 and Department guidelines as the basis for determining that this product conforms with Section 515. For purposes of compliance with Section 515, this CCSP Synthesis and Assessment Product is an "interpreted product" as that term is used in NOAA guidelines and is classified as "highly influential". This document does not express any regulatory policies of the United States or any of its agencies, or provide recommendations for regulatory action.



Weather and Climate Extremes in a Changing Climate

Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands

Synthesis and Assessment Product 3.3
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

EDITED BY:
Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol,
Anne M. Waple, and William L. Murray

June, 2008

Members of Congress:

On behalf of the National Science and Technology Council, the U.S. Climate Change Science Program (CCSP) is pleased to transmit to the President and the Congress this Synthesis and Assessment Product (SAP), *Weather and Climate Extremes in a Changing Climate, Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. This is part of a series of 21 SAPs produced by the CCSP aimed at providing current assessments of climate change science to inform public debate, policy, and operational decisions. These reports are also intended to help the CCSP develop future program research priorities.

The CCSP's guiding vision is to provide the Nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The SAPs are important steps toward achieving that vision and help to translate the CCSP's extensive observational and research database into informational tools that directly address key questions being asked of the research community.

This SAP assesses the state of our knowledge concerning changes in weather and climate extremes in North America and U.S. territories. It was developed with broad scientific input and in accordance with the Guidelines for Producing CCSP SAPs, the Federal Advisory Committee Act, the Information Quality Act, Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (Public Law 106-554), and the guidelines issued by the Department of Commerce and the National Oceanic and Atmospheric Administration pursuant to Section 515.

We commend the report's authors for both the thorough nature of their work and their adherence to an inclusive review process.

Sincerely,

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Chair, Committee on Climate Change Science and Technology Integration

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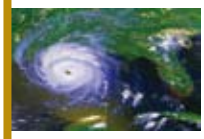

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CCSP Synthesis and Assessment Product 3.3 (SAP 3.3) was developed with the benefit of a scientifically rigorous, first draft peer review conducted by a committee appointed by the National Research Council (NRC). Prior to their delivery to the SAP 3.3 Author Team, the NRC review comments, in turn, were reviewed in draft form by a second group of highly qualified experts to ensure that the review met NRC standards. The resultant NRC Review Report was instrumental in shaping the final version of SAP 3.3, and in improving its completeness, sharpening its focus, communicating its conclusions and recommendations, and improving its general readability.

We wish to thank the members of the NRC Review Committee: John Gyakum (Co-Chair), McGill University, Montreal, Quebec; Hugh Willoughby (Co-Chair), Florida International University, Miami; Cortis Cooper, Chevron, San Ramon, California; Michael J. Hayes, University of Nebraska, Lincoln; Gregory Jenkins, Howard University, Washington, DC; David Karoly, University of Oklahoma, Norman; Richard Rotunno, National Center for Atmospheric Research, Boulder, Colorado; and Claudia Tebaldi, National Center for Atmospheric Research, Boulder Colorado, and Visiting Scientist, Stanford University, Stanford, California; and also the NRC Staff members who coordinated the process: Chris Elfring, Director, Board on Atmospheric Sciences and Climate; Curtis H. Marshall, Study Director; and Katherine Weller, Senior Program Assistant.

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Randy Dole (Earth System Research Laboratory)
Michelle Hawkins (Office of Program Planning and Integration)
Isaac Held (Geophysical Fluid Dynamics Laboratory)
Wayne Higgins (Climate Prediction Center)
Chris Landsea (National Hurricane Center)

The review process for SAP 3.3 also included a public review of the Second Draft, and we thank the individuals who participated in this cycle. The Author Team carefully considered all comments submitted, and a substantial number resulted in further improvements and clarity of SAP 3.3.

Finally, it should be noted that the respective review bodies were not asked to endorse the final version of SAP 3.3, as this was the responsibility of the National Science and Technology Council.

Changes in extreme weather and climate events have significant impacts and are among the most serious challenges to society in coping with a changing climate.

Many extremes and their associated impacts are now changing. For example, in recent decades most of North America has been experiencing more unusually hot days and nights, fewer unusually cold days and nights, and fewer frost days. Heavy downpours have become more frequent and intense. Droughts are becoming more severe in some regions, though there are no clear trends for North America as a whole. The power and frequency of Atlantic hurricanes have increased substantially in recent decades, though North American mainland land-falling hurricanes do not appear to have increased over the past century. Outside the tropics, storm tracks are shifting northward and the strongest storms are becoming even stronger.

It is well established through formal attribution studies that the global warming of the past 50 years is due primarily to human-induced increases in heat-trapping gases. Such studies have only recently been used to determine the causes of some changes in extremes at the scale of a continent. Certain aspects of observed increases in temperature extremes have been linked to human influences. The increase in heavy precipitation events is associated with an increase in water vapor, and the latter has been attributed to human-induced warming. No formal attribution studies for changes in drought severity in North America have been attempted. There is evidence suggesting a human contribution to recent changes in hurricane activity as well as in storms outside the tropics, though a confident assessment will require further study.

In the future, with continued global warming, heat waves and heavy downpours are very likely to further increase in frequency and intensity. Substantial areas of North America are likely to have more frequent droughts of greater severity. Hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase. The strongest cold season storms are likely to become more frequent, with stronger winds and more extreme wave heights.

Current and future impacts resulting from these changes depend not only on the changes in extremes, but also on responses by human and natural systems.

RECOMMENDED CITATIONS

For the Report as a whole:

CCSP, 2008: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol, Anne M. Waple, and William L. Murray (eds.)]. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA, 164 pp.

For the Preface:

Karl, T.R., G.A. Meehl, C.D. Miller, W.L. Murray, 2008: Preface in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

For the Executive Summary:

Karl, T.R., G.A. Meehl, T.C. Peterson, K.E. Kunkel, W.J. Gutowski, Jr., D.R. Easterling, 2008: Executive Summary in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

For Chapter 1:

Peterson, T.C., D.M. Anderson, S.J. Cohen, M. Cortez-Vázquez, R.J. Murnane, C. Parmesan, D. Phillips, R.S. Pulwarty, J.M.R. Stone, 2008: Why Weather and Climate Extremes Matter in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

For Chapter 2:

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For Chapter 3:

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For Chapter 4:

Easterling, D.R., D.M. Anderson, S.J. Cohen, W.J. Gutowski, G.J. Holland, K.E. Kunkel, T.C. Peterson, R.S. Pulwarty, R.J. Stouffer, M.F. Wehner, 2008: Measures to Improve Our Understanding of Weather and Climate Extremes in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

For Appendix A:

Smith, R.L., 2008: Statistical Trend Analysis in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Report Motivation and Guidance for Using this Synthesis/Assessment Report

Authors:
Thomas R. Karl, NOAA; Gerald A. Meehl, NCAR; Christopher D. Miller, NOAA; William L. Murray, STG, Inc.

According to the National Research Council, "an essential component of any research program is the periodic synthesis of cumulative knowledge and the evaluation of the implications of that knowledge for scientific research and policy formulation." The U.S. Climate Change Science Program (CCSP) is helping to meet that fundamental need through a series of 21 "synthesis and assessment products" (SAPs). A key component of the CCSP Strategic Plan (released July 2003), the SAPs integrate research results focused on important science issues and questions frequently raised by decision makers.

The SAPs support informed discussion and decisions by policymakers, resource managers, stakeholders, the media, and the general public. They are also used to help define and set the future direction and priorities of the program. The products help meet the requirements of the Global Change Research Act of 1990. The law directs agencies to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic scientific assessments. This SAP (3.3) provides an in-depth assessment of the state of our knowledge about changes in weather and climate extremes in North America (and U.S. territories), where we live, work, and grow much of our food.

The impact of weather and climate extremes can be severe and wide-ranging although, in some cases, the impact can also be beneficial. Weather and climate extremes affect all sectors of the economy and the environment, including human health and well-being. During the period 1980-2006, the U.S. experienced 70 weather-related disasters in which overall damages exceeded $1 billion at the time of the event. Clearly, the direct impact of extreme weather and climate events on the U.S. economy is substantial.

There is scientific evidence that a warming world will be accompanied by changes in the intensity, duration, frequency, and spatial extent of weather and climate extremes. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report has evaluated extreme weather and climate events on a global basis in the context of observed and projected changes in climate. However, prior to SAP 3.3 there has not been a specific assessment of observed and projected changes in weather and climate extremes across North America (including the U.S. territories in the Caribbean Sea and the Pacific Ocean), where observing systems are among the best in the world, and the extremes of weather and climate are some of the most notable occurring across the globe.

The term "weather extremes," as used in SAP 3.3, signifies individual weather events that are unusual in their occurrence (minimally, the event must lie in the upper or lower ten percentile of the distribution) or have destructive potential, such as hurricanes and tornadoes. The term "climate extremes" is used to represent the same type of event, but viewed over seasons (*e.g.*, droughts), or longer periods. In this assessment we are particularly interested in whether climate extremes are changing in terms of a variety of characteristics, including intensity, duration, frequency, or spatial extent, and how they are likely to evolve in the future, although, due to data limitations and the scarcity of published analyses, there is little that can be said about extreme events in Hawaii, the Caribbean, or the Pacific Islands outside of discussion of tropical cyclone intensity and frequency. It is often very difficult to attribute a particular climate or weather extreme, such as a single drought episode or a single severe hurricane, to a specific cause. It is more feasible to attribute the changing "risk" of extreme events to specific causes. For this reason,

this assessment focuses on the possible changes of past and future statistics of weather and climate extremes.

In doing any assessment, it is helpful to precisely convey the degree of certainty of important findings. For this reason, a lexicon expressing the likelihood of each key finding is presented below and used throughout this report. There is often considerable confusion as to what likelihood statements really represent. Are they statistical in nature? Do they consider the full spectrum of uncertainty or certainty? How reliable are they? Do they actually represent the true probability of occurrence, that is, when the probability states a 90% chance, does the event actually occur nine out of ten times?

There have been numerous approaches to address the problem of uncertainty. We considered a number of previously used methods, including the lexicon used in the IPCC Fourth Assessment (AR4), the US National Assessment of 2000, and previous Synthesis and Assessment Products, in particular SAP 1.1. SAP 1.1 was the first assessment to point out the importance of including both the statistical uncertainty related to finite samples and the "structural" uncertainty" related to the assumptions and limitations of physical and statistical models. This SAP adopted an approach very similar to that used in SAP 1.1 and the US National Assessment of 2000, with some small modifications (Preface Figure 1).

The likelihood scale in Figure 1 has fuzzy boundaries and is less discrete than the scale used in AR4. This is because the science of studying changes in climate extremes is not as well-developed as the study of changes in climate means over large space scales. The latter is an important topic addressed in IPCC. In addition, the AR4 adopted a confidence terminology which ranged from low confidence to medium confidence (5 chances in 10) to high confidence. As discussed in AR4, in practice, the confidence and likelihood statements are often linked. This is due in part to the limited opportunities we have in climate science to assess the confidence in our likelihood statements, in contrast to daily weather forecasts, where the reliability of forecasts based on expert judgment has been shown to be quite good. For example, the analysis of past forecasts have shown it does actually rain nine of ten times when a 90% chance of rain is predicted

It is important to consider both the uncertainty related to limited samples and the uncertainty of alternatives to fundamental assumptions. Because of these factors, and taking into account the proven reliability of weather forecast likelihood statements based on expert judgment, this SAP relies on the expert judgment of the authors for its likelihood statements.

Statements made without likelihood qualifiers, such as "will occur", are intended to indicate a high degree of certainty, *i.e.*, approaching 100%.

DEDICATION

This Climate Change and Synthesis Product is dedicated to the memory of our colleague, friend, and co-author Dr. Miguel Cortez-Vázquez whose untimely passing during the writing of the report was a loss to us all, both professionally and personally.

Figure P.1 Language in this Synthesis and Assessment Product used to express the team's expert judgment of likelihood.