

Abrupt Climate Change

U.S. Climate Change Science Program
Synthesis and Assessment Product 3.4

December 2008

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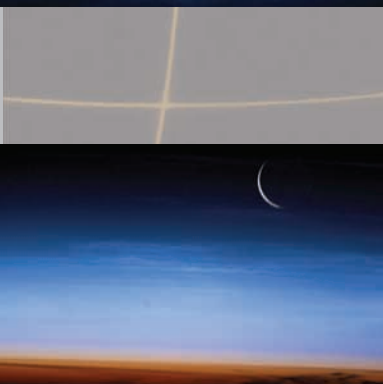
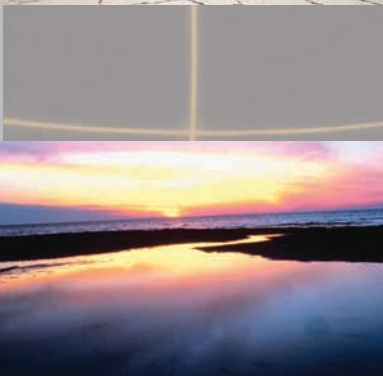
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This Synthesis and Assessment Product, described in the U.S. Climate Change Science Program (CCSP) Strategic Plan, was prepared in accordance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and the information quality act guidelines issued by the Department of the Interior and the U.S. Geological Survey pursuant to Section 515. The CCSP Interagency Committee relies on the Department of the Interior and the U.S. Geological Survey 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 U.S. Geological Survey 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.



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Synthesis and Assessment Product 3.4
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

Lead Agency

U.S. Geological Survey

Contributing Agencies

National Oceanic and Atmospheric Administration

National Science Foundation



December 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) *Abrupt Climate Change*. 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 abrupt climate change events where key aspects of the climate system change faster than the responsible forcings would suggest and/or faster than society can respond to those changes. It was developed in accordance with the Guidelines for Producing CCSP SAPs, 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 Interior and the U.S. Geological Survey 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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ACKNOWLEDGMENTS

In addition to the authors, many individuals made important contributions to this document.

The Product Lead and Other Agency Representatives would like to offer their special thanks to Thomas Armstrong and Patricia Jellison of the Office of Global Change at the USGS for their oversight, advice, and editorial diligence at every stage in the development of this report.

We are grateful to the following individuals for peer reviewing this report: Jess F. Adkins, California Institute of Technology; Becky Alexander, University of Washington; Paul A. Baker, Duke University; Eric J. Barron, National Center for Atmospheric Research; Michael Bentley, University of Durham; Karen L. Bice, Woods Hole Oceanographic Institution; Robert Bindschadler, NASA Goddard Space Flight Center; Franco Biondi, University of Nevada; Cecilia Bitz, University of Washington; Harry Bryden, University of Southampton; Mark Bush, Florida Institute of Technology; Ruth Curry, Woods Hole Oceanographic Institution; R. Lawrence Edwards, University of Minnesota; Sherilyn C. Fritz, University of Nebraska; Yongsong Huang, Brown University; James Kennett, University of California; Michael E. Mann, Pennsylvania State University; Mark F. Meier, University of Colorado; Germán Mora, Iowa State University; Delia Oppo, Woods Hole Oceanographic Institution; David K. Rea, University of Michigan; William Ruddiman, University of Virginia; Gavin Schmidt, NASA Goddard Institute for Space Studies; and Eli Tziperman, Harvard University. Details of the peer review process can be found at http://www.usgs.gov/peer_review/docs/sap3-4_pr_results.pdf.

We are also grateful to all the reviewers who provided valuable comments during the public comment period. The draft manuscript, public review comments and responses by the authors can be found at <http://www.climate-science.gov/Library/sap/sap3-4/default.php>.

The high quality layout of this report would not be possible without the expert editorial support of John Watson, Kay Hedrick, and Anna Glover of the Enterprise Publishing Network at the USGS. Stephen Elmore at George Mason University and Danielle Eganhouse at George Washington University also made important fact-checking and graphical contributions to the document.

Thanks to Karen Wood and Arlene Compher of the USGS Office of Communications for their sound advice and assistance in ensuring that the various drafts of this report were effectively disseminated to reviewers, stakeholders, policy makers, and the general public. Thanks also to Caroline Miller at the USGS for her administrative support and to the facilitation team of Tricia Gibbons and Kathleen Cleary of Lead Alliance.

Finally, we wish to thank all of the workshop participants who helped jump-start this process in March of 2007.

RECOMMENDED CITATIONS

For the Report as a whole:

CCSP, 2008: *Abrupt Climate Change*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Clark, P.U., A.J. Weaver (coordinating lead authors), E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (chapter lead authors)]. U.S. Geological Survey, Reston, VA, 244 pp.

For the Preface:

McGeehin, J.P., J.A. Barron, D.M. Anderson, and D.J. Verardo, 2008: Preface. In: *Abrupt Climate Change*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. VIII–X.

For the Executive Summary:

Clark, P.U., A.J. Weaver, E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen, 2008: Executive Summary. In: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 1–7.

For Chapter 1:

Clark, P.U., A.J. Weaver, E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen, 2008: Introduction: Abrupt changes in the Earth's climate system. In: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 9–27.

For Chapter 2:

Steffen, K., P.U. Clark, J.G. Cogley, D. Holland, S. Marshall, E. Rignot, and R. Thomas, 2008: Rapid changes in glaciers and ice sheets and their impacts on sea level. In: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 29–66.

For Chapter 3:

Cook, E.R., P.J. Bartlein, N. Diffenbaugh, R. Seager, B.N. Shuman, R.S. Webb, J.W. Williams, and C. Woodhouse, 2008: Hydrological variability and change. In: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 67–115.

For Chapter 4:

Delworth, T.L., P.U. Clark, M. Holland, W.E. Johns, T. Kuhlbrodt, J. Lynch-Stieglitz, C. Morrill, R. Seager, A.J. Weaver, and R. Zhang, 2008: The potential for abrupt change in the Atlantic Meridional Overturning Circulation. In: *Abrupt Climate Change*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 117–162.

For Chapter 5:

Brook, E., D. Archer, E. Dlugokencky, S. Frolking, and D. Lawrence, 2008: Potential for abrupt changes in atmospheric methane. In: *Abrupt Climate Change*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 163–201.



For this Synthesis and Assessment Report, abrupt climate change is defined as:

A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

This report considers progress in understanding four types of abrupt change in the paleoclimatic record that stand out as being so rapid and large in their impact that if they were to recur, they would pose clear risks to society in terms of our ability to adapt: (1) rapid change in glaciers, ice sheets, and hence sea level; (2) widespread and sustained changes to the hydrologic cycle; (3) abrupt change in the northward flow of warm, salty water in the upper layers of the Atlantic Ocean associated with the Atlantic Meridional Overturning Circulation (AMOC); and (4) rapid release to the atmosphere of methane trapped in permafrost and on continental margins.

This report reflects the significant progress in understanding abrupt climate change that has been made since the report by the National Research Council in 2002 on this topic, and this report provides considerably greater detail and insight on these issues than did the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). New paleoclimatic reconstructions have been developed that provide greater understanding of patterns and mechanisms of past abrupt climate change in the ocean and on land, and new observations are further revealing unanticipated rapid dynamic changes of modern glaciers, ice sheets, and ice shelves as well as processes that are contributing to these changes. This report reviews this progress. A summary and explanation of the main results is presented first, followed by an overview of the types of abrupt climate change considered in this report. The subsequent chapters then address each of these types of abrupt climate change, including a synthesis of the current state of knowledge and an assessment of the likelihood that one of these abrupt changes may occur in response to human influences on the climate system.

Report Motivation and Guidance for Using this Synthesis and Assessment Report

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A primary objective of the U.S. Climate Change Science Program (CCSP) is to provide the best possible, up-to-date scientific information to support public discussion and government and private sector decision-making on key climate-related issues. To help meet this objective, the CCSP has identified a set of 21 synthesis and assessment products (SAP) to address its highest priority research, observation, and decision-support needs. This SAP (3.4) focuses on abrupt climate change events where key aspects of the climate system change faster than the responsible forcings would suggest and/or faster than society can respond to those changes.

This report addresses Goal 3 of the CCSP Strategic Plan: Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future. The report (1) summarizes the current knowledge of key climate parameters that could change abruptly in the near future, potentially within years to decades and (2) provides scientific information on these topics for decision support. As such, the SAP is aimed at both the decision-making audience and the expert scientific and stakeholder community.

Background

Past records of climate and environmental change derived from archives such as tree rings, ice cores, corals, and sediments indicate that global and regional climate has experienced repeated abrupt changes, many occurring over a time span of decades or less. Abrupt climate changes might have a natural cause (such as volcanic aerosol forcing), an anthropogenic cause (such as increasing carbon dioxide in the atmosphere), or might be unforced (related to internal climate variability). Regardless of the cause, abrupt climate change presents potential risks for society that are poorly understood. An improved ability to understand and model future abrupt climate change is essential to provide decision-makers with the information they need to plan for these potentially significant changes.

The National Research Council (NRC) report "Abrupt Climate Change" (Alley *et al.*, 2002) provides an excellent treatise on this topic. Additionally, the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) (IPCC, 2007) addresses many of the same topics associated with abrupt climate change. This SAP picks up where the NRC report and the IPCC AR4 leave off, updating the state and strength of existing knowledge, both from the paleoclimate and historical records, as well as from model predictions for future change.

Focus of this Synthesis and Assessment Product

The content of this report follows a prospectus that was developed by the SAP Product Advisory Group, made up of the co-authors of this preface. The prospectus is available from the CCSP website (<http://www.climate-science.gov>).

SAP 3.4 considers four types of change documented in the paleoclimate record that stand out as being so rapid and large in their impact that they pose clear risks to society in terms of our ability to adapt. They are supported by sufficient evidence in current research indicating that abrupt changes could occur in the future. These four topics, each addressed as a chapter in this report, are

1. Rapid Changes in Glaciers and Ice Sheets and their Impacts on Sea Level;
2. Hydrological Variability and Change;
3. Potential for Abrupt Change in the Atlantic Meridional Overturning Circulation (AMOC); and
4. Potential for Abrupt Changes in Atmospheric Methane.

The following questions are considered in this report:

Rapid Changes in Glaciers and Ice Sheets and their Impacts on Sea Level

- What is the paleoclimate evidence regarding rates of rapid ice sheet melting?
- What are the recent rates and trends in ice sheet mass balance?
- What will be the impact on sea level if the recently observed rapid rates of melting continue?
- What is needed to model the mechanical processes that accelerate ice loss?

Hydrological Variability and Change

- What is our present understanding of the causes of major drought and hydrological change, including the role of the oceans or other natural or nongreenhouse-gas anthropogenic effects as well as land-use changes? (Note that this question is posed to facilitate an assessment of what is known about natural causes for hydrological change as opposed to anthropogenic causes, such as increased greenhouse gases. The authors also address anthropogenic influences, including greenhouse gases, as a potential source of hydrological change, in the past, present, and future.)
- What is our present understanding of the duration, extent, and causes of megadroughts of the past 2,000 years?
- What states of oceanic/atmospheric conditions and the strength of land-atmosphere coupling are likely to have been responsible for sustained megadroughts?
- How might such a state affect the climate in regions not affected by drought? (For example, enhanced floods or hurricanes in other regions.)
- What will be the change in the state of natural variability of the ocean and atmosphere that will signal the abrupt transition to a megadrought?

Potential for Abrupt Change in the Atlantic Meridional Overturning Circulation

- What are the factors that control the overturning circulation?
- How well do the current ocean general circulation models (and coupled atmosphere-ocean models) simulate the overturning circulation?
- What is the present state of the MOC?
- What is the evidence for change in the overturning circulation in the past?
- What are the global and regional impacts of a change in the overturning circulation?
- What factors that influence the overturning circulation are likely to change in the future, and what is the probability that the overturning circulation will change?

- What are the observational and modeling requirements required to understand the overturning circulation and evaluate future change?

Potential for Abrupt Changes in Atmospheric Methane

- What is the volume of methane stored in terrestrial and marine sources and how much of it is likely to be released in various climate change scenarios?
- What is the impact on the climate system of the release of varying quantities of methane over varying intervals of time?
- What is the evidence in the past for abrupt climate change caused by massive methane release?
- How much methane is likely to be released by thawing of the topmost layer (3 meters) of permafrost? Is thawing at greater depths likely to occur?
- What conditions (in terms of sea-level rise and warming of bottom waters) would allow methane release from hydrates in sea-floor sediments?
- What are the observational and modeling requirements necessary to understand methane storage and its release under various future scenarios of abrupt climate change?

Each section of this report is structured to answer these questions in the manner that best suits the topic. Questions are addressed either specifically as individual sections or subsections of a chapter, or through a broader, more systematic discussion of the topic. Additional subject matter is presented in a chapter, beyond what is asked for in the prospectus, where the authors feel that this information is necessary to effectively treat the topic.

It is important to note that the CCSP Synthesis and Assessment Products are scientific documents that are intended to be of use not only to scientists but to the American public and to decisionmakers within the United States. As such, the geographic focus of the Abrupt Climate Change SAP is United States, and by extension, North American climate. Other regional examples of abrupt climate change are discussed when the authors feel that the information serves as an important analog to past, present, or future North American climate.

Suggestions for Reading, Using, and Navigating this Report

This report is composed of four main chapters that correspond to the major climate themes indicated above. There is also an introductory chapter that provides an extensive overview of the information from the other four chapters, as well as additional background information. The Executive Summary further distills the information, with a focus on the key findings and recommendations from each chapter.

The four theme chapters have a recurring organizational format. Each chapter begins with key scientific findings which are then followed by recommendations for future research aimed at deepening our understanding of the critical scientific issues raised in the chapter. The scientific theories, models, data, and uncertainties that are part of the author's scientific syntheses and assessments are referenced through citations to peer-reviewed literature throughout the chapter. Finally, side boxes are used to discuss topics the author team felt deserved additional attention or served as useful case studies.

A reader interested in an overview of the state of the science for the topic of abrupt climate change might, therefore, start by reading the Executive Summary and Introduction chapter (Chapter 1) of this report, then delve deeper into the thematic chapters for more detailed explanations and information.

To integrate a wide variety of information and provide estimates of uncertainty associated with results, this report utilizes the terms from the IPCC AR4 (IPCC, 2007). Terms of uncertainty range from "exceptionally unlikely" (< 1% likelihood) to "virtually certain" (> 99% likelihood). See Box 1.1 in the Introduction chapter (Chapter 1) of this report for a complete explanation of the uncertainty terms.

The Synthesis and Assessment Product Team

The primary authors of this report were constituted as a Federal Advisory Committee that was charged with advising the USGS and the CCSP on the scientific and technical content related to the topic of abrupt climate change as described in the SAP 3.4 prospectus. (See Public Law 92-463 for more information on the Federal Advisory Committee Act, and the GSA website <http://fido.gov/facadatabase/> for specific information related to the SAP 3.4 Federal Advisory Committee.) The Federal Advisory Committee for SAP 3.4 enlisted input from numerous contributing authors. These authors provided substantial, relevant content to the report, but did not participate in the Federal Advisory Committee deliberations upon which this SAP was developed.

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- Alley, R.B., *et al.*, 2002: *Abrupt climate change: Inevitable surprises*. National Academy Press, Washington, DC, 244 pp.
- IPCC, 2007: *Climate change 2007. The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 996 pp.