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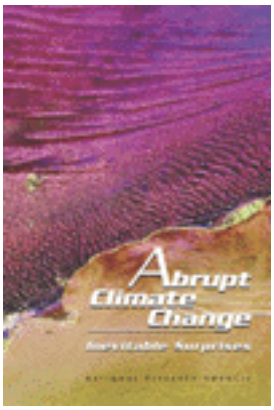

Abrupt Climate Change: Inevitable Surprises

Committee on Abrupt Climate Change, National Research Council

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The climate record for the past 100,000 years clearly indicates that the climate system has undergone periodic—and often extreme—shifts, sometimes in as little as a decade or less. The causes of abrupt climate changes have not been clearly established, but the triggering of events is likely to be the result of multiple natural processes. Abrupt climate changes of the magnitude seen in the past would have far-reaching implications for human society and ecosystems, including major impacts on energy consumption and water supply demands. Could such a change happen again? Are human activities exacerbating the likelihood of abrupt climate change? What are the potential societal consequences of such a change? Abrupt Climate Change: Inevitable Surprises looks at the current scientific evidence and theoretical understanding to describe what is currently known about abrupt climate change, including patterns and magnitudes, mechanisms, and probability of occurrence. It identifies critical knowledge gaps concerning the potential for future abrupt changes, including those aspects of change most important to society and economies, and outlines a research strategy to close those gaps. Based on the best and most current research available, this book surveys the history of climate change and makes a series of specific recommendations for the future.

Executive Summary

ecent scientific evidence shows that major and widespread climate changes have occurred with startling speed. For example, roughly half the north Atlantic warming since the last ice age was achieved in only a decade, and it was accompanied by significant climatic changes across most of the globe. Similar events, including local warmings as large as 16°C, occurred repeatedly during the slide into and climb out of the last ice age. Human civilizations arose after those extreme, global ice-age climate jumps. Severe droughts and other regional climate events during the current warm period have shown similar tendencies of abrupt onset and great persistence, often with adverse effects on societies.

Abrupt climate changes were especially common when the climate system was being forced to change most rapidly. Thus, greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events. The abrupt changes of the past are not fully explained yet, and climate models typically underestimate the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected.

The new paradigm of an abruptly changing climatic system has been well established by research over the last decade, but this new thinking is little known and scarcely appreciated in the wider community of natural and social scientists and policy-makers. At present, there is no plan for

improving our understanding of the issue, no research priorities have been identified, and no policy-making body is addressing the many concerns raised by the potential for abrupt climate change. Given these gaps, the US Global Change Research Program asked the National Research Council to establish the Committee on Abrupt Climate Change and charged the group to describe the current state of knowledge in the field and recommend ways to fill in the knowledge gaps.

It is important not to be fatalistic about the threats posed by abrupt climate change. Societies have faced both gradual and abrupt climate changes for millennia and have learned to adapt through various mechanisms, such as moving indoors, developing irrigation for crops, and migrating away from inhospitable regions. Nevertheless, because climate change will likely continue in the coming decades, denying the likelihood or downplaying the relevance of past abrupt events could be costly. Societies can take steps to face the potential for abrupt climate change. The committee believes that increased knowledge is the best way to improve the effectiveness of response, and thus that research into the causes, patterns, and likelihood of abrupt climate change can help reduce vulnerabilities and increase our adaptive capabilities. The committee's research recommendations fall into two broad categories: (1) implementation of targeted research to expand instrumental and paleoclimatic observations and (2) implementation of modeling and associated analysis of abrupt climate change and its potential ecological, economic, and social impacts. What follows is a summary of recommended research activities; more detail is presented in the chapters, particularly in Chapter 6.

IMPROVE THE FUNDAMENTAL KNOWLEDGE BASE RELATED TO ABRUPT CLIMATE CHANGE

Recommendation 1. Research programs should be initiated to collect data to improve understanding of thresholds and nonlinearities in geophysical, ecological, and economic systems. Geophysical efforts should focus especially on modes of coupled atmosphere-ocean behavior, oceanic deepwater processes, hydrology, and ice. Economic and ecological research should focus on understanding nonmarket and environmental issues, initiation of a comprehensive land-use census, and development of integrated economic and ecological data sets. These data will enhance understanding of abrupt

climate change impacts and will aid development of adaptation strategies.

Physical, ecological, and human systems are imperfectly understood, complex, nonlinear, and dynamic. Current changes in climate are producing conditions in these systems that are outside the range of recent historical experience and observation, and it is unclear how the systems will interact with and react to the coming climatic changes. Our ability to adapt to or mitigate the effects of climate change will be improved if we can recognize climate-related changes quickly. This will require improved monitoring of climatic, ecological, and socioeconomic systems. Many of the needed data sets overlap with those used to study gradual climate change.

To increase understanding of abrupt climate change, research should be directed toward aspects of the climate system that are believed to have participated in past abrupt changes or that are likely to exhibit abrupt and persistent changes when thresholds in the climate system are crossed. Key research areas for increasing our understanding of abrupt climate change include:

- oceanic circulation, especially related to deepwater formation;
- sea-ice transport and processes, particularly where they interact with deepwater formation;
- land-ice behavior, including conditions beneath ice sheets;
- the hydrological cycle, including storage, runoff, and permafrost changes; and
- modes of atmospheric behavior and how they change over time.

In the ecological and human sphere, data collection should target sectors where the impacts of abrupt climate change are likely to be largest or where knowledge of ongoing changes will be especially useful in understanding impacts and developing response alternatives. Data collection should include a comprehensive land-use census that monitors fragmentation of ecosystems, tracking of wildlife diseases, and conditions related to forest fires, as well as improved seasonal and long-term climate forecasts, and sustained study of oceanic regimes of intense biological activity, particularly near the coasts. In the social arena, priority should be given to development of environmental and nonmarket accounts, and analyses of possible threshold crossings.

IMPROVE MODELING FOCUSED ON ABRUPT CLIMATE CHANGE

Recommendation 2. New modeling efforts that integrate geophysical, ecological, and social-science analyses should be developed to focus on investigating abrupt climate changes. In addition, new mechanisms that can cause abrupt climate change should be investigated, especially those operating during warm climatic intervals. Understanding of such mechanisms should be improved by developing and applying a hierarchy of models, from theory and conceptual models through models of intermediate complexity, to high-resolution models of components of the climate system, to fully coupled earth-system models. Model-data comparisons should be enhanced by improving the ability of models to simulate changes in quantities such as isotopic ratios that record past climatic conditions. Modeling should be used to generate scenarios of abrupt climate change with high spatial and temporal resolution for assessing impacts and testing possible adaptations. Enhanced, dedicated computational resources will be required for such modeling.

Developing theoretical and empirical models to understand abrupt climate changes and the interaction of such changes with ecological and economic systems is a high priority. Modeling is essential for collaborative research between physical, ecological, and social scientists, and much more effort is needed to develop accurate models that produce a useful understanding of abrupt climate processes. Model analyses help to focus research on possible causes of abrupt climate change, such as human activities; on key areas where climatic thresholds might be crossed; and on fundamental uncertainties in climate-system dynamics. To date, most analyses have considered only gradual climate change; given the accumulating evidence of past abrupt climate change and of its capacity to affect human societies, more attention should be focused on scenarios involving abrupt change.

Climate models that are used to test leading hypotheses for abrupt climate change, such as altered deep-ocean circulation, can only partially simulate the size, speed, and extent of the large climatic changes that have occurred. The failure to explain the climate record fully suggests either that the proposed mechanisms being used to drive these models are incomplete or that the models are not as sensitive to abrupt climate change as is the natural environment. It is also of concern that existing models do not accurately simulate warm climates of the past.

A comprehensive modeling strategy designed to address abrupt climate change should include vigorous use of a hierarchy of models, from theory and conceptual models through models of intermediate complexity, to high-resolution models of components of the climate system, to fully coupled earth-system models. The simpler models are well suited for use in developing new hypotheses for abrupt climate change and should focus on warmer climate, because warming is likely. Because reorganizations of the thermohaline circulation have never been demonstrated in climate models employing high-resolution ocean components, improving the spatial resolution in climate models assumes high priority. Complex models should be used to produce geographically resolved (to about 1° of latitude by 1° of longitude), short-time (annual or seasonal) sensitivity experiments and scenarios of possible abrupt climatic changes.

Long integrations of fully coupled models under various forcings for the past, present, and future are needed to evaluate the models, assess possibilities of future abrupt changes, and provide scenarios of those future changes. The scenarios can be combined with integrated-assessment economic models to improve understanding of the costs for alternative adaptive approaches to climate change with attention to the effects of rising greenhouse-gas concentrations and nonclimatic factors, such as land-use changes and urbanization. Model-data comparisons are needed to assess the quality of model predictions. It is important to note that the multiple long integrations of enhanced, fully coupled earth-system models required for this research are not possible with the computer resources available today, and thus these resources should be enhanced.

IMPROVE PALEOCLIMATIC DATA RELATED TO ABRUPT CLIMATE CHANGE

Recommendation 3. The quantity of paleoclimatic data on abrupt change and ecological responses should be enhanced, with special emphasis on:

- Selected coordinated projects to produce especially robust, multiparameter, high-resolution histories of climate change and ecological response.
- Better geographic coverage and higher temporal resolution.
- Additional proxies, including those that focus on water (e.g., droughts, floods, etc.).

- Multidisciplinary studies of selected abrupt climate changes.

The current scientific emphasis on abrupt climate change was motivated by strong evidence in proxy records that showed extreme climatic changes in the past, sometimes occurring within periods of fewer than 10 years. Paleoclimatic records provide important information related to changes in many environmental variables. However, not all proxy archives provide equally high confidence for estimating past climatic conditions, such as temperature and precipitation, and for determining when and how rapidly changes occurred.

Confidence can be improved by encouraging coordinated, multi-parameter, multi-investigator study of selected archives that have seasonal to decadal time accuracy and resolution, substantial duplication of measurements to demonstrate reproducibility, and extensive calibration of the relation between climate and sedimentary characteristics. As one example, in the ice-core projects from central Greenland, duplication of the measurements by independent, international teams provides exceptional confidence in most data and reveals which data sets do not warrant confidence. Sampling at very high time resolution to produce data sets complementary to those of other investigators gives an exceptionally clear picture of past climate. Such projects require more funding and effort than are typical of paleoclimatic research, but they provide an essential reference standard of abrupt climate change to which other records can be compared. A difficulty is that this reference standard is from one place in high northern latitudes and is inappropriate for study of much of the climate system.

Not all paleoclimatic records can be studied in the same detail as those from Greenland, but generation of at least a few similar highly resolved (preferably annually or subannually) reference standards including a North Atlantic marine record comparable with Greenland records, would be of great value. The ultimate goal is to develop a global network of records with at least decadal resolution. Terrestrial and marine records of climate change and ecological response from the regions of the western Pacific warm pool (the warmest part of the global climate system) and the Southern Ocean and Antarctic continent (the southern cold pole of the climate system) are among the most critical targets for future paleoclimate research, including generation of reference standards.

Abrupt climate change is likely to influence water availability and therefore is of great concern for economic and ecological systems. Focus on measures of precipitation, evaporation, and the quantitative difference between them is particularly important. Freshwater balance is also important

in controlling water density and thus the thermohaline circulation of the oceans; reconstructions of water-mass density in polar and subpolar regions are central. New methods for investigating past changes in the hydrological cycle are important, as are additional studies of the relation between a range of climatic changes and the signals they leave in sedimentary archives.

Global maps of past climates, with high resolution in time and space and spanning long intervals, would be of great use to the climate community. However, such maps are unlikely to be available soon. The traditional alternative of reconstructing climate for selected moments, or "time-slices," fails to capture the short-lived anomalies of abrupt climate changes. Instead, mapping efforts are needed and should focus on the patterns of selected abrupt climatic changes in time and space and on their resulting effects. Additional emphasis on annually resolved records of the last 2,000 years will help to place the warming and associated changes of the last 100 years in context.

IMPROVE STATISTICAL APPROACHES

Recommendation 4. Current practices in the development and use of statistics related to climate and climate-related variables generally assume a simple, unchanging distribution of outcomes. This assumption leads to serious underestimation of the likelihood of extreme events. The conceptual basis and the application of climatic statistics should be re-examined with an eye to providing realistic estimates of the likelihood of extreme events.

Many societal decisions are based on assumptions about the distribution of extreme weather-related events. Large capital projects, for instance, often have embedded safety margins that are derived from data and assumptions about the frequency distribution of extreme events. Many major decisions are based on statistical calculations that are appropriate for stationary climates, such as in the use of "30-year normals," for deriving climate data for individual locations.

On the whole, those assumptions are reasonable, if imperfect, rules of thumb to use when the variability of weather is small and climate is stationary. If climate follows normal distributions with known and constant means and standard deviations, businesses and governments can use current practices. However, in light of recent findings related to nonstationary and of-

ten highly skewed climate-related variables, current practices can be misleading and result in costly errors.

The potential for abrupt climate change and the existence of thresholds for its effects require revisions of our statistical estimates and practices.

INVESTIGATE "NO-REGRETS" STRATEGIES TO REDUCE VULNERABILITY

Recommendation 5. Research should be undertaken to identify "no-regrets" measures to reduce vulnerabilities and increase adaptive capacity at little or no cost. No-regrets measures may include low-cost steps to: slow climate change; improve climate forecasting; slow biodiversity loss; improve water, land, and air quality; and develop institutions that are more robust to major disruptions. Technological changes may increase the adaptability and resiliency of market and ecological systems faced by the prospect of damaging abrupt climate change. Research is particularly needed to assist poor countries, which lack both scientific resources and economic infrastructure to reduce their vulnerabilities to potential abrupt climate changes.

Social and ecological systems have long dealt with climate variability by taking steps to reduce vulnerability to its effects. The rapidity of abrupt climate change makes adaptation more difficult. By moving research and policy in directions that will increase the adaptability of economic and ecological systems, it might be possible to reduce vulnerability and increase adaptation at little or no cost. Many current policies and practices are likely to be inadequate in a world of rapid and unforeseen climatic changes. Improving these policies will be beneficial even if abrupt climate change turns out to fit a best-case, rather than a worst-case, scenario. Societies will have "no regrets" about the new policies, because they will be good policies regardless of the magnitude of environmental change. For example, the phaseout of chloroflourocarbons and replacement by gases with shorter atmospheric lifetimes have reduced the US contribution to global warming while at the same time reducing future health risks posed by ozone depletion.

In land-use and coastal planning, managers should consider the effects on ecosystem services that could result from interaction of abrupt climate changes with changes caused by people. Scientists and government organi-

zations at various levels may be used to develop and implement regulations and policies that reduce environmental degradation of water, air, and biota. Conservation measures related to land and watersheds might be put into place to reduce the rate of biotic invasions, with management strategies used to limit the spread of invasions. The potential economic and ecological costs of disease emerging from abrupt climate change should be assessed.

A promising option is to improve institutions to allow societies to withstand the greater risks associated with abrupt changes in climate. For example, water systems are likely to be stressed by abrupt climate change; to manage scarce water, it might prove beneficial to seek more flexible ways to allocate water, such as through use of water markets. Another example of a "no-regrets" strategy is insurance against the financial impacts of fires, floods, storms, and hurricanes. Through the development of new instruments, such as weather derivatives and catastrophe bonds, markets might better accommodate extreme events such as the effects of abrupt climate change. It will be important to investigate the development of better instruments to spread large losses that result from extreme events, priced realistically to reflect the risks but not to encourage excessive risk taking.

Because of the strength of existing infrastructure and institutions, the United States and other wealthy nations are likely to cope with the effects of abrupt climate change more easily than poorer countries. That does not mean that developed countries can remain isolated from the rest of the world, however. With growing globalization, adverse impacts—although likely to vary from region to region because exposure and sensitivity will vary—are likely to spill across national boundaries, through human and biotic migration, economic shocks, and political aftershocks. Thus, even though this report focuses primarily on the United States, the issues are global and it will be important to give attention to the issues faced by poorer countries that are likely to be especially vulnerable to the social and economic impacts of abrupt climate change.

The United States is uniquely positioned to provide both scientific and financial leadership, and to work collaboratively with scientists around the world, to gain better understanding of the global impacts of abrupt climate change as well as reducing the vulnerability and increasing the adaptation in countries that are particularly vulnerable to these changes. Many of the recommendations in this report, although currently aimed at US institutions, would apply throughout the world.

Abrupt Climate Change

Inevitable Surprises

Committee on Abrupt Climate Change
Ocean Studies Board
Polar Research Board
Board on Atmospheric Sciences and Climate
Division on Earth and Life Studies
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Cover: This Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) image provided by NASA JPL and acquired from the Space Shuttle Endeavour, STS-59 (April 11, 1994), shows part of the vast Namib Sand Sea on the west coast of southern Africa, just northeast of the city of Luderitz, Namibia. This region receives only a few centimeters of rain per year. The colors are assigned to different radar frequencies. The magenta areas in the image are fields of sand dunes, and the orange area along the bottom is the surface of the South Atlantic Ocean. The bright green features in the upper right are rocky hills protruding through the sand sea. Because this radar penetrates through the sand, it can reveal sub-surface features such as former lakes, rivers, and drainage channels that have long since dried up as the climate changed. SIR-C/X-SAR is a joint US-German-Italian project that captures sophisticated images of Earth that are useful to scientists from many disciplines. (NASA JPL image).

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Preface

arge, abrupt climate changes have repeatedly affected much or all of the earth, locally reaching as much as 10°C change in 10 years. Available evidence suggests that abrupt climate changes are not only possible but likely in the future, potentially with large impacts on ecosystems and societies.

This report is an attempt to describe what is known about abrupt climate changes and their impacts, based on paleoclimate proxies, historical observations, and modeling. The report does not focus on large, abrupt causes—nuclear wars or giant meteorite impacts—but rather on the surprising new findings that abrupt climate change can occur when gradual causes push the earth system across a threshold. Just as the slowly increasing pressure of a finger eventually flips a switch and turns on a light, the slow effects of drifting continents or wobbling orbits or changing atmospheric composition may "switch" the climate to a new state. And, just as a moving hand is more likely than a stationary one to encounter and flip a switch, faster earth-system changes—whether natural or human-caused—are likely to increase the probability of encountering a threshold that triggers a still faster climate shift.

We do not yet understand abrupt climate changes well enough to predict them. The models used to project future climate changes and their impacts are not especially good at simulating the size, speed, and extent of

the past changes, casting uncertainties on assessments of potential future changes. Thus, it is likely that climate surprises await us.

When orbital wiggles and rising greenhouse gases warmed the earth from the last ice age, proxy records show that smooth changes were interspersed with abrupt coolings and warmings, wettings and dryings. By analogy, the expected future warming may come smoothly, but may come with jumps, short-lived or local coolings, floods or droughts, and other unexpected changes. Societies and ecosystems have an easier time dealing with slower or better-anticipated changes, so the abruptness and unpredictability of the possible changes may be disquieting.

This report considers patterns, magnitudes, mechanisms, and impacts of abrupt climate changes, possible implications for the future, and critical knowledge gaps. The potentially large impacts and prediction difficulties focus special attention on increasing the adaptability and resiliency of societies and ecosystems. The committee notes that there is no need to be fatalistic; human and natural systems have survived many abrupt changes in the past, and will continue to do so. Nonetheless, future dislocations can be minimized by taking steps to face the potential for abrupt climate change. The committee believes that increased knowledge is the best way to improve the effectiveness of response, and thus that research on abrupt climate change can help reduce vulnerabilities and increase adaptive capabilities.

I would like to thank the US Global Change Research Program and staff at the many agencies who are a part of USGCRP, for funding and participating in this study process. Thanks also to the Yale/NBER Program on International Environmental Economics for additional funding, and to committee members Bill Nordhaus and Dorothy Peteet for organizing and conducting the Impacts Workshop. The numerous participants at our workshops, the reviewers, and many other colleagues contributed valuable insights and encouragement. It has been my privilege to work with Study Director Alexandra Isern (now with the National Science Foundation), Polar Research Board Director Chris Elfring, Research Associate John Dandelski, and with Senior Project Assistants Megan Kelly, Jodi Bachim, and Ann Carlisle, of the National Research Council. I thank the Ocean Studies Board, the Polar Research Board, and the Board on Atmospheric Science and Climate for providing the impetus to do this study and oversight throughout the process.

I would especially like to extend my deep appreciation to the committee's members for their efforts in creating this report. By exploring

new territory and working across disciplines, the committee has opened my eyes to exciting new frontiers. I hope that the readers of this report join us in seeing not peril but opportunity for improved knowledge leading toward a happier and more secure future.

Richard B. Alley, *Chair*
Committee On Abrupt Climate Change

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Knox (Scripps Institution of Oceanography) and Stephen Berry (University of Chicago), appointed by the National Research Council, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Abrupt Climate Change