Executive Summary

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Main Results and Findings

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. While these four types of change pose clear risks to human and natural systems, this report does not focus on specific effects on these systems as a result of abrupt change.

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 (IPCC) Fourth Assessment Report (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 moderns 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. Throughout this report we have adopted the IPCC terminology in our expert assessment of the likelihood of a particular outcome or result. The term *virtually certain* implies a >99% probability; *extremely likely*: >95% probability; *very likely*: > 90% probability; *likely*: >65% probability; *more likely than not*: >50% probability; *about as likely as not*: 33%–66% probability; *unlikely*: <33% probability; *very unlikely*: < 10% probability; *extremely unlikely*: <5% probability; *exceptionally unlikely*: <1%.

Based on an assessment of the published scientific literature, the primary conclusions presented in this report are:

- Recent rapid changes at the edges of the Greenland and West Antarctic ice sheets show acceleration of flow and thinning, with the velocity of some glaciers increasing more than twofold. Glacier accelerations causing this imbalance have been related to enhanced surface meltwater production penetrating to the bed to lubricate glacier motion, and to ice-shelf removal, ice-front retreat, and glacier ungrounding that reduce resistance to flow. The present generation of models does not capture these processes. It is unclear whether this imbalance is a short-term natural adjustment or a response to recent climate change, but processes causing accelerations are enabled by warming, so these adjustments will very likely become more frequent in a warmer climate. The regions likely to experience future rapid changes in ice volume are those where ice is grounded well below sea level such as the West Antarctic Ice Sheet or large glaciers in Greenland like the Jakobshavn Isbrae that flow into the sea through a deep channel reaching far inland. Inclusion of these processes in models will likely lead to sea-level projections for the end of the 21st century that substantially exceed the projections presented in the IPCC AR4 report (0.28 ± 0.10 m to 0.42 ± 0.16 m rise).

- There is no clear evidence to date of human-induced global climate change on North American precipitation amounts. However, since the IPCC AR4 report, further analysis of climate model scenarios of future hydroclimatic change over North America and the global subtropics indicate that subtropical aridity is likely to intensify and persist due to future greenhouse warming. This projected drying extends poleward into the United States Southwest, potentially increasing the likelihood of severe and persistent drought there in the future. If the model results are correct then this drying may have already begun, but currently cannot be definitively identified amidst the considerable natural variability of hydroclimate in Southwestern North America.

- The AMOC is the northward flow of warm, salty water in the upper layers of the Atlantic, and the southward flow of colder water in the deep Atlantic. It plays an important role in the oceanic transport of heat from low to high latitudes. It is very likely that the strength of the AMOC will decrease over the course of the 21st century in response to increasing greenhouse gases, with a best estimate decrease of 25-30%. However, it is very unlikely that the AMOC will undergo an abrupt transition to a weakened state or collapse during the course of the 21st century, and it is unlikely that the AMOC will collapse beyond the end of the 21st century because of global warming, although the possibility cannot be entirely excluded.

- A dramatic abrupt release of methane (CH_4) to the atmosphere appears very unlikely, but it is very likely that climate change will accelerate the pace of persistent emissions from both hydrate sources and wetlands. Current models suggest that a doubling of northern high latitudes CH_4 emissions could be realized fairly easily. However, since these models do not realistically represent all the processes thought to be relevant to future northern high-latitude CH_4 emissions, much larger (or smaller) increases cannot be discounted. Acceleration of release from hydrate reservoirs is likely, but its magnitude is difficult to estimate.

Major Questions and Related Findings

1. Will There Be an Abrupt Change in Sea Level?

This question is addressed in Chapter 2 of this report, with emphasis on documenting (1) the recent rates and trends in the net glacier and ice-sheet annual gain or loss of ice/snow (known as mass balance) and their contribution to sea level rise (SLR) and (2) the processes responsible for the observed acceleration in ice loss from marginal regions of existing ice sheets. In response to this question, Chapter 2 notes:

1. The record of past changes in ice volume provides important insight to the response of large ice sheets to climate change.
    - Paleorecords demonstrate that there is a strong inverse relation between atmospheric carbon dioxide (CO_2) and global ice volume. Sea level rise associated with the melting of the ice sheets at the end of the last Ice Age ~20,000 years ago averaged 10-20 millimeters per year (mm a^{-1}) with large "meltwater fluxes" exceeding SLR of 50 mm a^{-1} and lasting several centuries, clearly demonstrating the potential for ice sheets to cause rapid and large sea level changes.
2. Sea level rise from glaciers and ice sheets has accelerated.
    - Observations demonstrate that it is extremely likely that the Greenland Ice Sheet is losing mass and that this has very likely been accelerating since the mid-1990s. Greenland has been thickening at high elevations because of the increase in snowfall that is consistent with high-latitude warming, but this gain is more than offset by an accelerating mass loss, with a large component from rapidly thinning and accelerating outlet glaciers. The balance between

gains and losses of mass decreased from near-zero in the early 1990s to net losses of 100 gigatonnes per year (Gt a^{-1}) to more than 200 Gt a^{-1} for the most recent observations in 2006.

- The mass balance for Antarctica is a net loss of about 80 Gt a^{-1} in the mid 1990s, increasing to almost 130 Gt a^{-1} in the mid 2000s. Observations show that while some higher elevation regions are thickening, substantial ice losses from West Antarctica and the Antarctic Peninsula are very likely caused by changing ice dynamics.

  - The best estimate of the current (2007) mass balance of small glaciers and ice caps is a loss that is at least three times greater (380 to 400 Gt a^{-1}) than the net loss that has been characteristic since the mid-19th century.

3. Recent observations of the ice sheets have shown that changes in ice dynamics can occur far more rapidly than previously suspected.

   - Recent observations show a high correlation between periods of heavy surface melting and increase in glacier velocity. A possible cause is rapid meltwater drainage to the base of the glacier, where it enhances basal sliding. An increase in meltwater production in a warmer climate will likely have major consequences on ice-flow rate and mass loss.

   - Recent rapid changes in marginal regions of the Greenland and West Antarctic ice sheets show mainly acceleration and thinning, with some glacier velocities increasing more than twofold. Many of these glacier accelerations closely followed reduction or loss of their floating extensions known as ice shelves. Significant changes in ice-shelf thickness are most readily caused by changes in basal melting induced by oceanic warming. The interaction of warm waters with the periphery of the large ice sheets represents one of the most significant possibilities for abrupt change in the climate system. The likely sensitive regions for future rapid changes in ice volume by this process are those where ice is grounded well below sea level, such as the West Antarctic Ice Sheet or large outlet glaciers in Greenland like the Jakobshavn Isbrae that flow through a deep channel that extends far inland.

- Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low.

2. Will There Be an Abrupt Change in Land Hydrology?

This question is addressed in Chapter 3 of this report. In general, variations in water supply and in particular protracted droughts are among the greatest natural hazards facing the United States and the globe today and in the foreseeable future. In contrast to floods, which reflect both previous conditions and current meteorological events, and which are consequently more localized in time and space, droughts occur on subcontinental to continental scales and can persist for decades and even centuries.

On interannual to decadal time scales, droughts can develop faster than human societies can adapt to the change. Thus, a severe drought lasting several years can be regarded as an abrupt change, although it may not reflect a permanent change in the state of the climate system.

Empirical studies and climate model experiments conclusively show that droughts over North America and around the world are significantly influenced by the state of tropical sea-surface temperatures (SSTs), with cool La Niña-like SSTs in the eastern equatorial Pacific being especially responsible for the development of droughts over the southwestern United States and northern Mexico. Warm subtropical North Atlantic SSTs played a role in forcing the 1930s Dust Bowl and 1950s droughts as well. Unusually warm Indo-Pacific SSTs have also been strongly implicated in the development of global patterns of drought observed in recent years.

Historic droughts over North America have been severe, but not nearly as prolonged as a series of “megadroughts” reconstructed from tree rings from about A.D. 900 up to about A.D. 1600. These megadroughts are significant because they occurred in a climate system that was not being perturbed in a major way by human activity (i.e., the ongoing anthropogenic changes in greenhouse gas concentrations, atmospheric dust loadings, and land-cover changes). Modeling experiments indicate that these megadroughts may have occurred in response to cold tropical Pacific SSTs and warm subtropical North Atlantic SSTs externally forced by high irradiance and weak volcanic activity. However, this result is tentative, and the exceptional duration of the droughts has not been adequately explained, nor whether they also involved forcing from SST changes in other ocean basins.

Even larger and more persistent changes in hydroclimatic variability worldwide are indicated over the last 10,000 years by a diverse set of paleoclimatic indicators. The climate conditions associated with those changes were quite different from those of the past millennium and today, but they show the additional range of natural variability and truly abrupt hydroclimatic change that can be expressed by the climate system.

With respect to this question, Chapter 3 concludes:

- There is no clear evidence to date of human-induced global climate change on North American precipitation amounts. However, since the IPCC AR4 report, further analysis of climate model scenarios of future hydroclimatic change over North America and the global subtropics indicate that subtropical aridity is likely to intensify and persist due to future greenhouse warming. This projected drying extends poleward into the United States Southwest, potentially increasing the likelihood of severe and persistent drought there in the future. If the model results are correct then this drying may have already begun, but currently cannot be definitively identified amidst the considerable natural variability of hydroclimate in Southwestern North America.
- The cause of model-projected subtropical drying is an overall widespread warming of the ocean and atmosphere, in contrast to the causes of historic droughts, and the likely causes of Medieval megadroughts, which were related to changes in the patterns of SSTs. However, systematic biases within current coupled atmosphere-ocean models raise concerns as to whether they correctly represent the response of the tropical climate system to radiative forcing and whether greenhouse forcing will actually induce El Nino/Southern Oscillation-

like patterns of tropical SST change that will create impacts on global hydroclimate in addition to those caused by overall warming.

3. Do We Expect an Abrupt Change in the Atlantic Meridional Overturning Circulation?

This question is addressed in Chapter 4 of this report. The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the Earth's climate system, characterized by a northward flow of warm, salty water in the upper layers of the Atlantic, and a southward flow of colder water in the deep Atlantic. This ocean current system transports a substantial amount of heat from the Tropics and Southern Hemisphere toward the North Atlantic, where the heat is transferred to the atmosphere. Changes in this ocean circulation could have a profound impact on many aspects of the global climate system.

There is growing evidence that fluctuations in Atlantic sea surface temperatures, hypothesized to be related to fluctuations in the AMOC, have played a prominent role in significant climate fluctuations around the globe on a variety of time scales. Evidence from the instrumental record shows pronounced, multidecadal swings in widespread Atlantic temperature that may be at least partly due to fluctuations in the AMOC. Evidence from paleorecords suggests that there have been large, decadal-scale changes in the AMOC, particularly during glacial times. These abrupt changes have had a profound impact on climate, both locally in the Atlantic and in remote locations around the globe.

At its northern boundary, the AMOC interacts with the circulation of the Arctic Ocean. The summer arctic sea ice cover has undergone dramatic retreat since satellite records began in 1979, amounting to a loss of almost 30% of the September ice cover in 29 years. The late summer ice extent in 2007 was particularly startling and broke the previous record minimum with an extent that was three standard deviations below the linear trend. Conditions over the 2007-2008 winter promoted further loss of multiyear ice due to anomalous transport through Fram Strait, raising the possibility that rapid and sustained ice loss could result. Climate model simulations suggest that rapid and sustained September arctic ice loss is likely in future 21st century climate projections.

In response to the question of an abrupt change in the AMOC, Chapter 4 notes:

- It is very likely that the strength of the AMOC will decrease over the course of the 21st century in response to increasing greenhouse gases, with a best estimate decrease of 25-30%.
- Even with the projected moderate AMOC weakening, it is still very likely that on multidecadal to century time scales a warming trend will occur over most of the European region downstream of the North Atlantic Current in response to increasing greenhouse gases, as well as over North America.
- It is very unlikely that the AMOC will undergo a collapse or an abrupt transition to a weakened state during the 21st century.
- It is also unlikely that the AMOC will collapse beyond the end of the 21st century because of global warming, although the possibility cannot be entirely excluded.
- Although it is very unlikely that the AMOC will collapse in the 21st century, the potential consequences of this event could be severe. These might include a southward shift of the tropical rainfall belts, additional sea level rise around the North Atlantic, and disruptions to marine ecosystems.

4. What Is the Potential for Abrupt Changes in Atmospheric Methane?

This question is addressed in Chapter 5 of this report. The main concerns about abrupt changes in atmospheric methane stem from (1) the large quantity of methane believed to be stored in clathrate hydrates in the sea floor and to a lesser extent in permafrost soils and (2) climate-driven changes in emissions from northern high-latitude and tropical wetlands. The size of the hydrate reservoir is uncertain, perhaps by up to a factor of 10. Because the size of the reservoir is directly related to the perceived risks, it is difficult to make certain judgment about those risks.

Observations show that there have not yet been significant increases in methane emissions from northern high-latitude hydrates and wetlands resulting from increasing arctic temperatures. Although there are a number of suggestions in the literature about the possibility of a dramatic abrupt release of methane to the atmosphere, modeling and isotopic fingerprinting of ice-core methane do not support such a release to the atmosphere over the last 100,000 years or in the near future. Previous suggestions of a large release of methane at the Paleocene-Eeocene boundary (about 55 million years ago) face a number of objections, but may still be viable.

In response to the question of an abrupt increase in atmospheric methane, Chapter 5 notes:

- While the risk of catastrophic release of methane to the atmosphere in the next century appears very unlikely, it is very likely that climate change will accelerate the pace of persistent emissions from both hydrate sources and wetlands. Current models suggest that wetland emissions could double in the next century. However, since these models do not realistically represent all the processes thought to be relevant to future northern high-latitude CH_4 emissions, much larger (or smaller) increases cannot be discounted. Acceleration of persistent release from hydrate reservoirs is likely, but its magnitude is difficult to estimate.

Recommendations

How can the understanding of the potential for abrupt changes be improved?

We answer this question with nine primary recommendations that are required to substantially improve our understanding of the likelihood of an abrupt change occurring in the future. An overarching recommendation is the urgent need for committed and sustained monitoring of those components of the climate system identified in this report that are particularly vulnerable to abrupt climate change. The nine primary recommendations are:

1. Efforts should be made to (i) reduce uncertainties in estimates of mass balance and (ii) derive better measurements of glacier and ice-sheet topography and velocity through improved observation of glaciers and ice sheets. This includes continuing mass-balance measurements on small glaciers and completing the World Glacier Inventory. This further includes observing flow rates of glaciers and ice sheets from satellites, and sustaining aircraft observations of surface

elevation and ice thickness to ensure that such information is acquired at the high spatial resolution that cannot be obtained from satellites.

2. Address shortcomings in ice-sheet models currently lacking proper representation of the physics of the processes likely to be most important in potentially causing an abrupt loss of ice and resulting sea level rise. This will significantly improve the prediction of future sea level rise.
3. Research is needed to improve existing capabilities to forecast short- and long-term drought conditions and to make this information more useful and timely for decision making to reduce drought impacts. In the future, drought forecasts should be based on an objective multimodel ensemble prediction system to enhance their reliability and the types of information should be expanded to include soil moisture, runoff, and hydrological variables.
4. Improved understanding of the dynamic causes of long-term changes in oceanic conditions, the atmospheric responses to these ocean conditions, and the role of soil moisture feedbacks are needed to advance drought prediction capabilities. Ensemble drought prediction is needed to maximize forecast skill, and “downscaling” is needed to bring coarse-resolution drought forecasts from General Circulation Models down to the resolution of a watershed.
5. Efforts should be made to improve the theoretical understanding of the processes controlling the AMOC, including its inherent variability and stability, especially with respect to climate change. This will likely be accomplished through synthesis studies combining models and observational results.
6. Improve long-term monitoring of the AMOC. Parallel efforts should be made to more confidently predict the future behavior of the AMOC and the risk of an abrupt change. Such a prediction system should include advanced computer models, systems to start model predictions from the observed climate state, and projections of future changes in greenhouse gases and other agents that affect the Earth’s energy balance.
7. Prioritize the monitoring of atmospheric methane abundance and its isotopic composition with spatial density sufficient to allow detection of any change in net emissions from northern and tropical wetland regions. The feasibility of

monitoring methane in the ocean water column or in the atmosphere to detect emissions from the hydrate reservoir should be investigated. Efforts are needed to reduce uncertainties in the size of the global methane hydrate reservoir in marine and terrestrial environments and to identify the size and location of hydrate reservoirs that are most vulnerable to climate change.

8. Additional modeling efforts should be focused on (i) processes involved in releasing methane from the hydrate reservoir and (ii) the current and future climate-driven acceleration of release of methane from wetlands and terrestrial hydrate deposits.
9. Improve understanding of past abrupt changes through the collection and analysis of those proxy records that most effectively document past abrupt changes in sea level, ice-sheet and glacier extent, distribution of drought, the AMOC, and methane, and their impacts.