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 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 (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 dynamical 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* 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 its motion, and ice-shelf removal, ice-front retreat, and glacier ungrounding that reduce resistance to flow. The present generation of models do 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).

- Climate model scenarios of future hydroclimatic change over North America and the global subtropics indicate that subtropical aridity will likely intensify and persist due to future greenhouse warming. This drying is likely to extend poleward into the American West, thus increasing the likelihood of severe and persistent drought there in the future. If the model results are correct then this drying is likely to have already begun.
- 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 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 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 (SLR) 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 1990's 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 as a whole is close to balance, but with a likely small net loss since 2000. Observations show that while some higher elevation regions are thickening, likely as a result of high interannual

variability in snowfall, 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 flows 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 sea level projections 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 American West 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 by major changes in its boundary conditions such as increasing greenhouse gas concentrations. 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 boundary 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:

- Climate model scenarios of future hydroclimatic change over North America and the global subtropics indicate that subtropical aridity will likely intensify and persist due to future greenhouse warming. This drying is likely to extend poleward into the American West, thus increasing the likelihood of severe and persistent drought there in the future. If the model results are correct then this drying is likely to have already begun.
- 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.

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 eight 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 eight primary recommendations are:

1. Efforts should be made to improve observing systems of glaciers and ice sheets in order to (i) reduce uncertainties in estimates of mass balance and (ii) derive better measurements of glacier and ice-sheet topography and velocity. This includes maintaining and extending established programs, both governmental and university-based, of mass-balance measurements on small glaciers, and completing the World Glacier Inventory through programs such as the Global Land Ice Measurements from Space (GLIMS) program. This further includes developing and implementing satellite missions (e.g. InSAR and IceSAT-II) to observe flow rates of glaciers and ice sheets, 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. Current ice-sheet models lack proper representation of the physics of the processes suggested by modern observations as being the most important in potentially causing an abrupt loss of ice and resulting sea level rise. Emphasis should be given to a committed national-level ice-sheet modeling effort aimed at addressing these shortcomings and thereby significantly improving 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 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. Deployment of a sustained, decades-long observation system for the AMOC is needed to properly characterize and monitor the AMOC. Parallel efforts should be made to develop a system to more confidently predict the future behavior of the AMOC and the risk of an abrupt change. Such a prediction system will 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. Monitoring of atmospheric methane abundance and its isotopic composition should be maintained and expanded 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.