Chapter 1. Introduction: Abrupt Changes in the Earth's Climate System

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1. Background

Ongoing and projected growth in global population and its attendant demand for carbon-based energy is placing human societies and natural ecosystems at ever-increasing risk to climate change (*IPCC, 2007*). In order to mitigate this risk, the United Nations Framework Convention on Climate Change (UNFCCC) would stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent "dangerous anthropogenic interference" with the climate system (*UNFCCC, 1992*, Article 2). Successful implementation of this objective requires that such a level be achieved "within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (*UNFCCC, 1992*, Article 2).

Among the various aspects of the climate change problem, the rate of climate change is clearly important in determining whether proposed implementation measures to stabilize GHG concentrations are adequate to allow sufficient time for mitigation and adaptation. In particular, the notion of adaptation and vulnerability takes on a new meaning when considering the possibility that the response of the climate system to radiative forcing[†] from increased GHG concentrations may be abrupt. Because the societal, economic, and ecological impacts of such an abrupt climate change would be far greater than for the case of a gradual change, assessing the likelihood of an abrupt, or nonlinear, climate response becomes critical to evaluating what constitutes dangerous human interference (*Alley et al., 2003*).

Studies of past climate demonstrate that abrupt changes have occurred frequently in Earth history, even in the absence of radiative forcing. Although geologic records of abrupt change have been available for decades, the decisive evidence that triggered widespread scientific and public interest in this behavior of the climate system came in the early 1990's with the publication of climate records from long ice cores from the Greenland Ice Sheet (Fig. 1.1). Subsequent development of marine and terrestrial records (Fig. 1.1) that also resolve changes on these short time scales has yielded a wide variety of climate signals from highly resolved and well-dated records from which the following generalizations can be drawn:

- abrupt climate change is a fundamental characteristic of the climate system;
- some past changes were subcontinental to global in extent;
- the largest of these changes occurred during times of greater-than-present global ice volume;
- all components of the Earth's climate system (ocean, atmosphere, cyrosphere, biosphere) were involved in the largest changes, indicating a closely coupled system response with important feedbacks.

These developments have led to an intensive effort by climate scientists to understand the possible mechanisms of abrupt climate change. This effort is motivated by the fact that if

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[†] The term "forcing" is used throughout this Report to indicate any mechanism that causes the climate system to change, or respond. As defined by the IPCC Third Assessment Report (Church et al., 2001), **radiative forcing** refers to a change in the net radiation at the top of the troposphere caused by a change in the solar radiation, the infrared radiation, or other changes that affect the radiation energy absorbed by the surface (e.g., changes in surface reflection properties), resulting in a radiation imbalance. A positive radiative forcing tends to warm the surface on average, whereas a negative radiative forcing tends to cool it. Changes in GHG concentrations represent a radiative forcing through their absorption and emission of infrared radiation.

such large changes were to recur, they would have a potentially devastating impact on human society and natural ecosystems because of their inability to adapt on such short time scales. While past abrupt changes occurred in response to natural forcings, or were unforced, the prospect that human influences on the climate system may trigger similar abrupt changes in the near future (*Broecker, 1997*) adds further urgency to the topic.

Significant progress has been made since the report on abrupt climate change by the National Research Council (NRC) in 2002 (*NRC, 2002*), and this report provides considerably greater detail and insight on many of these issues than was provided in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (*IPCC, 2007*). New paleoclimate 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 modern glaciers, ice sheets, and ice shelves as well as processes that are contributing to these changes. Finally, improvements in modeling of the climate system have further reduced uncertainties in assessing the likelihood of an abrupt change. The present report reviews this progress.

2. Definition of Abrupt Climate Change

What is meant by abrupt climate change? Several definitions exist, with subtle but important differences. *Clark et al. (2002)* defined abrupt climate change as “a persistent transition of climate (over subcontinental scale) that occurs on the timescale of decades.” The NRC report “Abrupt Climate Change” (*NRC, 2002*) offered two definitions of abrupt climate change. A mechanistic definition defines abrupt climate change as occurring when “the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause.” This definition implies that abrupt climate changes involve a threshold or nonlinear feedback within the climate system from one steady state to another, but is not restrictive to the short time scale (1-100 years) that has clear societal and ecological implications. Accordingly, the NRC report also provided an impacts-based definition of abrupt climate change as “one that takes place so rapidly and unexpectedly that human or natural systems have difficulty adapting to it.” Finally, *Overpeck and Cole (2006)* defined abrupt climate change as "a transition in the climate system whose duration is fast relative to the duration of the preceding or subsequent state." Similar to the NRC's mechanistic definition, this definition transcends many possible time scales, and thus includes many different behaviors of the climate system that would have little or no detrimental impact on human (economic, social) systems and ecosystems.

For this report, we have modified and combined these definitions into one that emphasizes both the short time scale and the impact on ecosystems. In what follows we define abrupt climate change 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.

3. Organization of Report

Synthesis and Assessment Product 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 the ability of society and ecosystems to adapt. These changes are (i) rapid decrease in ice sheet mass with resulting global sea level rise; (ii) widespread and sustained changes to the hydrologic cycle that induces drought; (iii) changes in the Atlantic meridional overturning circulation (AMOC); and (iv) rapid release to the atmosphere of the potent greenhouse gas methane, which is trapped in permafrost and on continental slopes. Based on the published scientific literature, each chapter examines one of these types of change (sea level, drought, AMOC, and methane), providing a detailed assessment of the likelihood of future abrupt change as derived from reconstructions of past changes, observations and modeling of the present physical systems that are subject to abrupt change, and where possible, climate model simulations of future behavior of changes in response to increased GHG concentrations. In providing this assessment, we adopt the IPCC AR4 standard terms used to define the likelihood of an outcome or result where this can be determined probabilistically (Box 1.1).

4. Abrupt Change in Sea Level

Population densities in coastal regions and on islands are about three times higher than the global average, with approximately 23% of the world's population living within 100 kilometers (km) distance of the coast and <100 meters (m) above sea level (*Nicholls et al., 2007*). This allows even small sea level rise to have significant societal and economic impacts through coastal erosion, increased susceptibility to storm surges and resulting flooding, ground-water contamination by salt intrusion, loss of coastal wetlands, and other issues (Fig. 1.2).

An increase in global sea level largely reflects a contribution from water expansion from warming, and from the melting of land ice which dominates the actual addition of water to the oceans. Over the last century, the global average sea level rose at a rate of ~1.7 ± 0.5 millimeters per year (mm yr^{-1}). However, the rate of global sea level rise for the period 1993 to 2003 accelerated to 3.1 ± 0.7 mm yr^{-1}, reflecting either variability on decadal time scales or an increase in the longer term trend. Relative to the period 1961-2003, estimates of the contributions from thermal expansion and from glaciers and ice sheets indicate that increases in both of these sources contributed to the acceleration in global sea level rise that characterized the 1992-2003 period (*Bindoff et al., 2007*).

By the end of the 21st century, and in the absence of ice-dynamical contributions, the IPCC AR4 projects sea level to rise by 0.28 ± 0.10 m to 0.42 ± 0.16 m in response to additional global warming, with the contribution from thermal expansion accounting for 70-75% of this rise (*Meehl et al., 2007*). Projections for contributions from ice sheets are based on models that emphasize accumulation and surface melting in controlling the amount of mass gained and lost by ice sheets (mass balance), with different relative contributions for the Greenland and Antarctic ice sheets. Because the increase in mass loss (ablation) is greater than the increase in mass gain (accumulation), the Greenland Ice Sheet is projected to contribute to a positive sea level rise and may melt entirely from future global warming (*Ridley et al., 2005*). In contrast, the Antarctic Ice Sheet is projected to grow through increased accumulation relative to ablation and thus contribute to a negative sea level rise. The net projected effect on global sea level from these two differing ice-sheet responses to global warming over the remainder of this century is to nearly cancel each other out. Accordingly, the primary contribution to sea-level rise from projected mass changes in the IPCC AR4 is associated with retreat of glaciers and ice caps (*Meehl et al., 2007*).

Rahmstorf (2007) used the relation between 20th-century sea level rise and global mean surface temperature increase to predict a sea level rise of 0.5 to 1.4 m above the 1990 level by the end of the 21st century, considerably higher than the projections by the IPCC AR4 (*Meehl et al., 2007*). Insofar as the contribution to 20th century sea level rise from melting land ice is thought to have been dominated by glaciers and ice caps (*Bindoff et al., 2007*), the *Rahmstorf (2007)* projection does not include the possible contribution to sea level rise from ice sheets.

Recent observations of startling changes at the margins of the Greenland and Antarctic ice sheets indicate that dynamic responses to warming may play a much greater role in the future mass balance of ice sheets than considered in current numerical projections of sea level rise. Ice-sheet models used as the basis for the IPCC AR4 numerical projections did not include the physical processes that may be governing these dynamical responses, but if they prove to be significant to the long-term mass balance of the ice sheets, sea level projections will likely need to be revised upwards substantially. By implicitly excluding the potential contribution from ice sheets, the *Rahmstorf (2007)* estimate will also likely need to be revised upwards if dynamical processes cause future ice-sheet mass balance to become more negative.

Chapter 2 of this report summarizes the available evidence for recent changes in the mass of glaciers and ice sheets. The Greenland Ice Sheet is losing mass and very likely on an accelerated path since the mid-1990s. Observations show that Greenland is thickening at high elevations, because of an increase in snowfall, but that this gain is more than offset by an accelerating mass loss at the coastal margins, with a large component from rapidly thinning and accelerating outlet glaciers. The mass balance of the Greenland Ice Sheet during the period with good observations indicates that the loss increased from 100 gigatonnes per year (Gt a^{-1}) (where 360 Gt of ice = 1 mm of sea level) in the late 1990s to more than 200 Gt a^{-1} for the most recent observations in 2006.

Determination of the mass budget of the Antarctic ice sheet is not as advanced as that for Greenland. The mass balance for Antarctica as a whole has likely experienced a net loss since 2000 at rates of a few tens of Gt a^{-1} that are increasing with time, but with uncertainty of a similar magnitude to the estimated amount. There is little surface melting in Antarctica, but substantial ice losses are occurring from West Antarctica and the Antarctic Peninsula primarily in response to changing ice dynamics.

The record of past changes provides important insight to the behavior of large ice sheets during warming. At the last glacial maximum about 21,000 years ago, ice volume and area were more than twice modern. Deglaciation was forced by warming from changes in the Earth's orbital parameters, increasing greenhouse gas concentrations, and attendant feedbacks. Deglacial sea level rise averaged 10 mm a^{-1}, but with variations including two extraordinary episodes at 19 thousand years ago (ka) and 14.5 ka when peak rates potentially exceeded 50 mm a^{-1} (*Fairbanks, 1989; Yokoyama et al., 2000*). Each of these "meltwater pulses" added the equivalent of 1.5 to 3 Greenland ice sheets (7 m) to the oceans over a one- to five-century period, clearly demonstrating the potential for ice sheets to cause rapid and large sea level changes.

The primary factor that raises concerns about the potential of future abrupt changes in sea level is that large areas of modern ice sheets are currently grounded below sea level. Where it exists, it is this condition that lends itself to many of the processes that can lead to rapid ice-sheet changes, especially with regard to atmosphere-ocean-ice interactions that may affect ice shelves and calving fronts of glaciers terminating in water (tidewater glaciers). An important aspect of these marine-based ice sheets is that the beds of ice sheets grounded below sea level tend to deepen inland. The grounding line is the critical juncture that separates ice that is thick enough to remain grounded from either an ice shelf or a calving front. In the absence of stabilizing factors, this configuration indicated that marine ice sheets are inherently unstable, whereby small changes in climate could trigger irreversible retreat of the grounding line.

The amount of retreat clearly depends on how far inland glaciers remain below sea level. Of greatest concern is the West Antarctic Ice Sheet, with 5 to 6 m sea level equivalent, where much of the base of the ice sheet is grounded well below sea level, with deeper trenches lying well inland of their grounding lines. A similar situation applies to the entire Wilkes Land sector of East Antarctica. In Greenland, a number of outlet glaciers remain below sea level, indicating that glacier retreat by this process will continue for some time. A notable example is Greenland's largest outlet glacier, Jakobshavn Isbrae, which appears to tap into the central region of Greenland that is below sea level.

The key requirement for stabilizing grounding lines of marine-based ice sheets appears to be the presence of an extension of floating ice beyond the grounding line, referred to as an ice shelf. A thinning ice shelf results in ice-sheet ungrounding, which is the main cause of the ice acceleration because it has a large effect on the force balance near the ice front. Recent rapid changes in marginal regions of both ice sheets are characterized mainly by acceleration and thinning, with some glacier velocities increasing more than twofold. Many of these glacier accelerations closely followed reduction or loss of ice shelves. If glacier acceleration caused by thinning ice shelves can be sustained over many centuries, sea level will rise more rapidly than currently estimated.

Such behavior was predicted almost 30 years ago by *Mercer (1978)*, but was discounted as recently as the IPCC Third Assessment Report (*Church et al., 2001*) by most of the glaciological community based largely on results from prevailing model simulations. Considerable effort is now underway to improve the models, but it is far from complete, leaving us unable to make reliable predictions of ice-sheet responses to a warming climate if such glacier accelerations were to increase in size and frequency.

A nonlinear response of ice-shelf melting to increasing ocean temperatures is a central tenet in the scenario for abrupt sea-level rise arising from ocean – ice-shelf interactions. Significant changes in ice-shelf thickness are most readily caused by changes in basal melting. The susceptibility of ice shelves to high melt rates and to collapse is a function of the presence of warm waters entering the cavities beneath ice shelves. Future changes in ocean circulation and ocean temperatures will produce changes in basal melting, but the magnitude of these changes is currently neither modeled nor predicted.

Another mechanism that can potentially increase the sensitivity of ice sheets to climate change involves enhanced flow of the ice over its bed due to the presence of pressurized water, a process known as sliding. Where such basal flow is enabled, total ice flow rates may increase by 1-10 orders of magnitude, significantly decreasing the response time of an ice sheet to a climate or ice-marginal perturbation.

Recent data from Greenland show a high correlation between periods of heavy surface melting and an increase in glacier velocity (*Zwally et al., 2002*). A possible cause for this relation is rapid drainage of surface meltwater to the glacier bed, where it enhances lubrication and basal sliding. There has been a significant increase in meltwater runoff from the Greenland Ice Sheet for the 1998-2007 period compared to the previous three decades (Fig. 1.3). Total melt area is continuing to increase during the melt season and has already reached up to 50% of the Greenland Ice Sheet; further increase in Arctic temperatures will very likely continue this process and will add additional runoff. Because water represents such an important control on glacier flow, an increase in meltwater production in a warmer climate will likely have major consequences on flow rate and mass loss.

Because sites of global deepwater formation occur immediately adjacent to the Greenland and Antarctic ice sheets, any significant increase in freshwater fluxes from these ice sheets may induce changes in ocean heat transport and thus climate. This question is addressed in Chapter 4 of this report.

Summary

The Greenland and Antarctic Ice Sheets are losing mass, likely at an accelerating rate. Much of the loss from Greenland is by increased summer melting as temperatures rise, but an increasing proportion of the combined mass loss is caused by increasing ice discharge from the ice-sheet margins, indicating that dynamicalresponses to warming may play a much greater role in the future mass balance of ice sheets than previously considered. The interaction of warm waters with the periphery of the ice sheets is very likely one of the most significant mechanisms to trigger an abrupt rise in global sea level. The potentially sensitive regions for rapid changes in ice volume are thus likely those ice masses grounded below sea level such as the West Antarctic Ice Sheet or large glaciers in Greenland like the Jakobshavn Isbrae with an over-deepened channel reaching far inland. Ice-sheet models currently do not include the physical processes that may be governing these dynamical responses, so quantitative assessment of their possible contribution to sea level rise is not yet possible. If these processes prove to be significant to the long-term mass balance of the ice sheets, however, current sea level projections based on present-generation numerical models will likely need to be revised substantially upwards.

5. Abrupt Change in Land Hydrology

Much of the research on the climate response to increased GHG concentrations, and most of the public's understanding of that work, has been concerned with global warming. Accompanying this projected globally uniform increase in temperature, however, are spatially heterogeneous changes in water exchange between the atmosphere and the Earth's surface that are expected to vary much like the current daily mean values of precipitation and evaporation (*IPCC, 2007*). Although projected spatial patterns of hydroclimate change are complex, these projections suggest that many already wet areas are likely to get wetter and already dry areas are likely to get drier, while some intermediate regions on the poleward flanks of the current subtropical dry zones are likely to become increasingly arid.

These anticipated changes will increase problems at both extremes of the water cycle, stressing water supplies in many arid and semi-arid regions while worsening flood hazards and erosion in many wet areas. Moreover, the instrumental, historical and prehistorical record of hydrological variations indicates that transitions between extremes can occur rapidly relative to the time span under consideration. Over the course of several decades, for example, transitions between wet conditions and dry conditions may occur within a year and can persist for several years.

Abrupt changes or shifts in climate that lead to drought have had major impacts on societies in the past. Paleoclimatic data document rapid shifts to dry conditions that coincided with downfall of advanced and complex societies. The history of the rise and fall of several empires and societies in the Middle East between 7000 and 2000 B.C. have been linked to abrupt shifts to persistent drought conditions (*Weiss and Bradley, 2001*). Severe drought leading to crop failure and famine in the mid-8th century have been suggested as causes for the decline and collapse of the Tang Dynasty (*Yancheva et al., 2007*) and the Classic Maya (*Hodell et al., 1995*). A more recent example of the impact of severe and persistent drought on society is the 1930s Dust Bowl in the central United States (Fig. 1.4), which led to a large-scale migration of farmers from the Great Plains to the western United States. Societies in many parts of the world today may now be more insulated to the impacts of abrupt climate shifts in the form of drought through managed water resources and reservoir systems. Nevertheless, population growth and over-allocation of scarce water supplies in a number of regions have made societies even more vulnerable to the impacts of abrupt climate change involving drought.

Variations in water supply in general, and protracted droughts in particular, are among the greatest natural hazards facing the United States and the globe today and in the foreseeable future. According to the National Climatic Data Center, National Oceanic and Atmospheric Administration (NCDC, NOAA), over the period from 1980 to 2006 droughts and heatwaves were the second most expensive natural disaster in the U.S. behind tropical storms. The annual cost of drought to the U.S. is estimated to be in the billions of dollars. Although there is much uncertainty in these figures, it is clear that drought leads to (1) crop losses resulting in a loss of farm income and an increase in Federal disaster relief funds and food prices, (2) disruption of recreation and tourism, (3) increased fire risk and loss of life and property, (4) reduced hydroelectric energy generation, and (5) enforced water conservation to preserve essential municipal water supplies and aquatic ecosystems (Changnon et al., 2000; Pielke and Landsea, 1998; Ross and Lott, 2003).

5.1. History of North American Drought

In Chapter 3 of this report, we examine North American drought and its causes from the perspective of the historical record and, based on paleoclimate records, the last 1,000 years and the last 10,000 years. This longer temporal perspective relative to the historical record allows us to evaluate the natural range of drought variability under a diverse range of mean climatic conditions including those similar to the present.

Instrumental precipitation and temperature data and tree-ring analyses provide sufficient information to identify six serious multiyear droughts in western North America since 1856. Of these, the most famous is the 'Dust Bowl' drought that included most of the 1930s decade (Fig. 1.4). The other two in the 20th century are the severe drought in the Southwest from that late 1940s to the late 1950s and the drought that began in 1998 and is ongoing. Three droughts in the middle to late 19th century occurred (with approximate dates) from 1856 to 1865, from 1870 to 1876, and from 1890 to 1896.

Is the 1930s Dust Bowl drought the worst that can conceivably occur over North America? The instrumental and historical data only go back about 130 years with an acceptable degree of spatial completeness over the U.S., which does not provide us with enough time to characterize the full range of hydroclimatic variability that has happened in the past and could conceivably happen in the future independent of any added effects due to greenhouse warming. To do so, we must look beyond the historical data to longer natural archives of past climate information to gain a better understanding of the past occurrence of drought and its natural range of variability.

Much of what we have learned about the history of North American drought over the past 1,000 years is based on annual ring-width patterns of long-lived trees that are used to reconstruct summer drought based on the Palmer Drought Severity Index (PDSI). This information and other paleoclimate data have identified a period of elevated aridity during the "Medieval Climate Anomaly" (MCA) period (A.D. 900-1300) that included four particularly severe multi-decadal megadroughts (Fig. 1.5) (*Cook et al., 2004*). The range of annual drought variability during this period was not any larger than that seen after 1470, suggesting that the climate conditions responsible for these early droughts each year were apparently no more extreme than those conditions responsible for droughts during more recent times. This can be appreciated by noting that only 1 year of drought during the MCA was marginally more severe than the 1934 Dust Bowl year. This suggests that the 1934 event may be used as a worst-case scenario for how severe a given year of drought can get over the West. What sets these MCA megadroughts apart from droughts of more modern times, however, is their duration, with droughts during the MCA lasting much longer than historic droughts in the Western United States.

The emphasis up to now has been on the semi-arid to arid Western United States because that is where the late-20th century drought began and has largely persisted up to the present time. Yet, previous studies indicate that megadroughts have also occurred in the important crop-producing states in the Midwest and Great Plains as well (*Stahle et al., 2007*). In particular, a tree-ring PDSI reconstruction for the Great Plains shows the MCA period with even more persistent drought than the Southwest, but now on a centennial time scale.

Examination of drought history over the last 10,000 years (referred to as the Holocene Epoch) is motivated by noting that the projected changes in both the radiative forcing and the resulting climate of the 21st century far exceed those registered by either the instrumental records of the past century or by geologic archives that can be calibrated to derive climate (proxy records) of the past few millennia. In other words, all of the variations in climate over the instrumental period and over the past millennia reviewed above have occurred in a climate system whose controls have not differed much from those of the 20th century. Consequently, a longer term perspective is required to describe the behavior of the climate system under controls as different from those at present as those of the 21st century will be, and to assess the potential for abrupt climate changes to occur in response to gradual changes in large-scale forcing.

It is important to emphasize that the controls of climate during the 21st century and during the Holocene differ from one another, and from those of the 20th century, in important ways. The major difference in controls of climate between the early 20th, late 20th, and 21st century is in atmospheric composition (with an additional component of land-cover change). In contrast, the major difference between the controls in the 20th and 21st centuries and those in the early to middle Holocene is in the latitudinal and seasonal distribution of solar radiation. Accordingly, climatic variations during the Holocene should not be thought of either as analogs for future climates or as examples of what might be observable under present-day climate forcing if records were longer, but instead should be thought of as the result of a natural experiment within the climate system that features large perturbations of the controls of climate.

The paleoclimatic record from North America indicates that drier conditions than present commenced in the mid-continent between 10 and 8 thousand years ago (ka) (*Webb et al., 1993*), and ended after 4 ka. The variety of paleoenvironmental indicators reflect the spatial extent and timing of these moisture variations, and in general suggest that the dry conditions increased in their intensity during the interval from 11 ka to 8 ka, and then gave way to increased moisture after 4 ka. During the middle of this interval (around 6 ka) dry conditions were widespread. Lake-status indicators at 6 ka indicate lower-than-present levels (and hence drier-than-present conditions) across most of the continent, and quantitative interpretation of pollen data shows a similar pattern of overall aridity, but again with some regional and local variability, such as moister-than-present conditions in the Southwestern United States (*Williams et al., 2004*). Although the region of drier-than-present conditions extends into the Northeastern United States and eastern Canada, most of the evidence for mid-Holocene dryness is focused on the mid-continent, in particular the Great Plains and Midwest, where the evidence for aridity is particularly clear.

5.2. Causes of North American Drought

Empirical studies and climate model experiments show that droughts over North America and globally are significantly influenced by the state of tropical sea surface temperatures (SSTs), with cool, persistent La Niña-like SSTs in the eastern equatorial Pacific frequently causing development of droughts over the American West and northern Mexico. Climate models that have evaluated this linkage need only prescribe small changes in SSTs, no more than a fraction of a degree Celsius, to result in reductions in precipitation. It is the persistence of the SST anomalies and associated moisture deficits that creates serious drought conditions. In the Pacific, the SST anomalies presumably arise naturally from dynamics similar to those associated with the El Niño Southern Oscillation (ENSO) on time scales of a year to a decade (*Newman et al., 2003*). On long time scales, the dynamics that link tropical Pacific SST anomalies to North American hydroclimate appear as analogs of higher frequency phenomena associated with ENSO (*Shin et al., 2006*). In general, the atmospheric response to La Niña-like conditions forces descent of air over western North America that suppresses precipitation. In addition to the ocean influence, some modeling and observational estimates indicate that soil-moisture feedbacks also influence precipitation variability.

The causes of the MCA megadroughts appear to have similar origin to the causes of modern droughts, which is consistent with the similar spatial patterns expressed by MCA and modern droughts (*Herwijer et al., 2007*). In particular, 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 (*Mann et al., 2005; Emile-Geay et al., 2007*). 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.

Over longer time spans, the paleoclimatic record indicates that even larger hydrological changes have taken place in response to past changes in the controls of climate that rival in magnitude those predicted for the next several decades and centuries. These changes were driven ultimately by variations in the Earth's orbit that altered the seasonal and latitudinal distribution of incoming solar radiation. 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.

Summary

The paleoclimatic record reveals dramatic changes in North American hydroclimate over the last millennium that were not associated with changes in greenhouse gases and human-induced global warming. Accordingly, one important implication of these results is that because these megadroughts occurred under conditions not too unlike today's, the United States still has the capacity to enter into a prolonged state of dryness even in the absence of increased greenhouse-gas forcing.

In response to increased concentration of GHGs, the semi-arid regions of the Southwest are projected to dry in the 21st century, with the model results suggesting, if they are correct, that the transition is likely already underway (*Seager et al., 2007*). The drying in the Southwest is a matter of great concern because water resources in this region are already stretched, new development of resources will be extremely difficult, and the population and thus demand for water) continues to grow rapidly. Other subtropical regions of the world are also expected to dry in the near future, turning this feature of global hydroclimatic change into an international issue with potential impacts on migration and social stability. The mid-continental U.S. Great Plains could also experience changes in water supply impacting agricultural practices, grain exports, and biofuel production.

6. Abrupt Change in the Atlantic Meridional Overturning Circulation

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, a transformation of water mass properties at higher northern latitudes of the Atlantic in the Nordic and Labrador Seas that induces sinking of surface waters to form deep water, and a southward flow of colder water in the deep Atlantic (Fig. 1.6). There is also an interhemispheric transport of heat associated with this circulation, with heat transported from the Southern Hemisphere to the Northern Hemisphere. This ocean current system thus transports a substantial amount of heat from the Tropics and Southern Hemisphere toward the North Atlantic, where the heat is released to the atmosphere (Fig. 1.7).

Changes in the AMOC 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 (based on the last ~130 years) shows pronounced, multidecadal swings in large-scale Atlantic temperature that may be at least partly a consequence of fluctuations in the AMOC. Recent modeling and observational analyses have shown that these multidecadal shifts in Atlantic temperature exert a substantial influence on the climate system ranging from modulating African and Indian monsoonal rainfall to tropical Atlantic atmospheric circulation conditions of relevance for hurricanes. Atlantic SSTs also influence summer climate conditions over North America and Western Europe.

Evidence from paleorecords suggests that there have been large, decadal-scale changes in the AMOC, particularly during glacial times. These abrupt change events have had a profound impact on climate, both locally in the Atlantic and in remote locations around the globe (Fig. 1.1). Research suggests that these abrupt events were related to discharges of freshwater into the North Atlantic from surrounding land-based ice sheets. Subpolar North Atlantic air temperature changes of more than 10°C on time scales of a decade or two have been attributed to these abrupt change events.

6.1. Uncertainties in Modeling the AMOC

As with any projection of future behavior of the climate system, our understanding of the AMOC in the 21st century and beyond relies on numerical models that simulate the important physical processes governing the overturning circulation. An important test of model skill is to conduct transient simulations of the AMOC in response to the addition of freshwater and compare with paleoclimatic data. Such a test requires accurate, quantitative reconstructions of the freshwater forcing, including its volume, duration, and location, plus the magnitude and duration of the resulting reduction in the AMOC. This information is not easy to obtain; coupled general circulation model (GCM) simulations of most events have been forced with idealized freshwater pulses and compared with qualitative reconstructions of the AMOC (e.g., *Hewitt et al., 2006; Peltier et al., 2006;* see also *Stouffer et al., 2006*). There is somewhat more information about the freshwater pulse associated with an event 8200 years ago, but important uncertainties remain (*Clarke et al., 2004; Meissner and Clark, 2006*). Thus, simulations of such paleoclimatic events provide important qualitative perspectives on the ability of models to simulate the response of the AMOC to forcing changes, but their ability to provide quantitative assessments is limited. Improvements in this area would be an important advance, but the difficulty in measuring even the current AMOC makes this task daunting.

Although numerical models show good skill in reproducing the main features of the AMOC, there are known errors that occur that introduce uncertainty in model results. Some of these model errors, particularly in temperature and heat transport, are related to the representation of western boundary currents and deep-water overflow across the Greenland-Iceland-Scotland ridge. Increasing the resolution of current coupled ocean-atmosphere models to better address these errors will require an increase in computing power by an order of magnitude. Such higher resolution offers the potential of more realistic and robust treatment of key physical processes, including the representation of deep-water overflows. Efforts are being made to improve this model deficiency (*Willebrand et al., 2001; Thorpe et al., 2004; Tang and Roberts, 2005*). Nevertheless, recent work by *Spence et al. (2008)* using an Earth-system model of intermediate complexity (EMIC) found that the duration and maximum amplitude of their coupled model response to freshwater forcing showed little sensitivity to increasing resolution. They concluded that the coarse-resolution model response to boundary layer freshwater forcing remained robust at finer horizontal resolutions.

6.2. Future Changes in the AMOC

A particular focus on the AMOC in Chapter 4 of this report is to address the widespread notion, both in the scientific and popular literature, that a major weakening or even complete shutdown of the AMOC may occur in response to global warming. This discussion is driven in part by model results indicating that global warming tends to weaken the AMOC both by warming the upper ocean in the subpolar North Atlantic, and through increased freshwater input (by more precipitation, more river runoff, and melting inland ice) into the Arctic and North Atlantic. Both processes reduce the density of the upper ocean in the North Atlantic, thereby stabilizing the water column and weakening the AMOC.

It has been theorized that these processes could cause a weakening or shutdown of the AMOC that could significantly reduce the poleward transport of heat in the Atlantic, thereby possibly leading to regional cooling in the Atlantic and surrounding continental regions, particularly Western Europe. This mechanism can be inferred from paleodata and is reproduced at least qualitatively in the vast majority of climate models (*Stouffer et al., 2006*). One of the most misunderstood issues concerning the future of the AMOC under anthropogenic climate change, however, is its often-cited potential to cause the onset of the next ice age. As discussed by *Berger and Loutre (2002)* and *Weaver and Hillaire-Marcel (2004)*, it is not possible for global warming to cause an ice age by this mechanism.

In the past, there was disagreement in determining which of the two processes governing upper-ocean density will dominate under increasing GHG concentrations, but a recent 11-model intercomparison project found that a MOC reduction in response to increasing GHG concentrations was caused more by changes in surface heat flux than by changes in surface freshwater flux (*Gregory et al., 2005*). Nevertheless, different climate models show different sensitivities toward an imposed freshwater flux (*Gregory et al., 2005*). It is therefore not fully clear to what degree salinity changes will affect the total overturning rate of the AMOC. In addition, by today's knowledge, it is hard to assess how large future freshwater fluxes into the North Atlantic might be. This is due to uncertainties in modeling the hydrological cycle in the atmosphere, in modeling the sea-ice dynamics in the Arctic, as well as in estimating the melting rate of the Greenland ice sheet (see Chapter 2 of this report).

It is important to distinguish between an AMOC weakening and an AMOC collapse. Historically, coupled models that eventually lead to a collapse of the AMOC under global warming scenarios have fallen into two categories: (1) coupled atmosphere-ocean general circulation models (AOGCMs) that required ad hoc adjustments in heat or moisture fluxes to prevent them from drifting away from observations, and (2) intermediate-complexity models with longitudinally averaged ocean components. Current AOGCMs used in the IPCC AR4 assessment typically do not use flux adjustments, and incorporate improved physics and resolution. When forced with plausible estimates of future changes in greenhouse gases and aerosols, these newer models project a gradual 25-30% weakening of the AMOC, but not an abrupt change or collapse. Although a transient collapse with climatic impacts on the global scale can always be triggered in models by a large enough freshwater input (e.g., *Vellinga and Wood, 2007*), the magnitude of the required freshwater forcing is not currently viewed as a plausible estimate of the future. In addition, many experiments have been conducted with idealized forcing changes, in which atmospheric CO2 concentration is increased at a rate of 1%/year to either two times or four times the preindustrial levels and held fixed thereafter. In virtually every simulation, the AMOC reduces but recovers to its initial strength when the radiative forcing is stabilized at two times or four times the preindustrial levels.

Summary

Our analysis indicates that it is very likely that the strength of the AMOC will decrease over the course of the 21st century. In models where the AMOC weakens, warming still occurs downstream over Europe due to the radiative forcing associated with increasing greenhouse gases. No model under plausible estimates of future forcing exhibits an abrupt collapse of the MOC during the 21st century, even accounting for estimates of accelerated Greenland ice sheet melting. We conclude that it is very unlikely that the AMOC will abruptly weaken or collapse during the course of the 21st century. Based on available model simulations and sensitivity analyses, estimates of maximum Greenland ice sheet melting rates, and our understanding of mechanisms of abrupt climate change from the paleoclimatic record, we further conclude that it is unlikely that the AMOC will collapse beyond the end of the 21st century as a consequence of global warming, although the possibility cannot be entirely excluded.

The above conclusions depend upon our understanding of the climate system and on the ability of current models to simulate the climate system. An abrupt collapse of the AMOC in the 21st century would require either a sensitivity of the AMOC to forcing that is far greater than current models suggest or a forcing that greatly exceeds even the most aggressive of current projections (such as extremely rapid melting of the Greenland ice sheet). While we view these as very unlikely, we cannot exclude either possibility. Further, even if a collapse of the AMOC is very unlikely, the large climatic impacts of such an event, coupled with the significant climate impacts that even decadal scale AMOC fluctuations induce, argues for a strong research effort to develop the observations, understanding, and models required to predict more confidently the future evolution of the AMOC.

7. Abrupt Change in Atmospheric Methane Concentration

After carbon dioxide (CO_2), methane (CH_4) is the next most important greenhouse gas that humans directly influence. Methane is a potent greenhouse gas because it strongly absorbs terrestrial infrared (IR) radiation. Methane's atmospheric abundance has more than doubled since the start of the Industrial Revolution (*Etheridge et al., 1998; MacFarling Meure et al., 2006*), amounting to a total contribution to radiative forcing over this time of ~0.7 watts per square meter (W m^{-2}), or nearly half of that resulting from parallel increase in the atmospheric concentration of CO_2 (*Hansen and Sato, 2001*). Additionally, CO_2 produced by CH_4 oxidation is equivalent to ~6% of CO_2 emissions from fossil fuel combustion. Over a 100-year time horizon, the direct and indirect effects on radiative forcing from emission of 1 kg CH_4 are 25 times greater than for emission of 1 kg CO_2 (*IPCC, 2007*).

The primary geological reservoirs of methane that could be released abruptly to the atmosphere are found in ocean sediments and terrestrial soils as methane hydrate. Methane hydrate is a solid in which methane molecules are trapped in a lattice of water molecules (Fig. 1.8). On Earth, methane hydrate forms under high pressure – low temperature conditions in the presence of sufficient methane. These conditions are most often found in relatively shallow marine sediments on continental margins but also in some high-latitude soils (*Kvenvolden, 1993*). Estimates of the total amount of methane hydrate vary widely, from 500-10,000 gigatons of carbon (GtC) total stored as methane in hydrates in marine sediments, and 7.5-400 GtC in permafrost (both figures are uncertain). The total amount of carbon in the modern atmosphere is ~810 GtC, but the total methane content of the atmosphere is only ~4 GtC (*Dlugokencky et al., 1998*). Therefore, even a release of a small portion of the methane hydrate reservoir to the atmosphere could have a substantial impact on radiative forcing.

There is little evidence to support massive releases of methane from marine or terrestrial hydrates in the past. Evidence from the ice core record indicates that abrupt shifts in methane concentration have occurred in the past 110,000 years (*Brook et al., 1996*), but the concentration changes during these events were relatively small. Farther back in geologic time, an abrupt warming at the Paleocene-Eocene boundary about 55 million years ago has been attributed by some to a large release of methane to the atmosphere.

Concern about future abrupt release in atmospheric methane stems largely from the possibility that the massive amounts of methane present as solid methane hydrate in ocean sediments and terrestrial soils may become unstable in the face of global warming.

Warming or release of pressure can destabilize methane hydrate, forming free gas that may ultimately be released to the atmosphere (Fig. 1.9).

The processes controlling hydrate stability and gas transport are complex, and only partly understood. In Chapter 5 of this report, three categories of mechanisms are considered as potential causes of abrupt increases in atmospheric methane concentration in the near future. These are summarized in the following.

7.1. Destabilization of Marine Methane Hydrates

This issue is probably the most well known due to extensive research on the occurrence of methane hydrates in marine sediments, and the large quantities of methane apparently present in this solid phase in primarily continental margin marine sediments. Destabilization of this solid phase requires mechanisms for warming the deposits and/or reducing pressure on the appropriate time scale, transport of free methane gas to the sediment-water interface, and transport through the water column to the atmosphere (*Archer, 2007*). Warming of bottom waters, slope failure, and their interaction are the most commonly discussed mechanisms for abrupt release. However, bacteria are efficient at consuming methane in oxygen-rich sediments and the ocean water column, and there are a number of physical impediments to abrupt release from marine sediments.

On the time scale of the coming century, it is likely that most of the marine hydrate reservoir will be insulated from anthropogenic climate change. The exception is in shallow ocean sediments where methane gas is focused by subsurface migration. These deposits will very likely respond to anthropogenic climate change with an increased background rate of sustained methane release, rather than an abrupt release.

7.2. Destabilization of Permafrost Hydrates

Hydrate deposits at depth in permafrost soils are known to exist, and although their extent is uncertain, the total amount of methane in permafrost hydrates appears to be much smaller than in marine sediments. Surface warming eventually would increase melting rates of permafrost hydrates. Inundation of some deposits by warmer seawater and lateral invasion of the coastline are also concerns and may be mechanisms for more rapid change.

Destabilization of hydrates in permafrost by global warming is unlikely over the next few centuries (*Harvey and Huang, 1995*). No mechanisms have been proposed for the abrupt release of significant quantities of methane from terrestrial hydrates (*Archer, 2007*). Slow and perhaps sustained release from permafrost regions may occur over decades to centuries from mining extraction of methane from terrestrial hydrates in the arctic (*Boswell, 2007*), over decades to centuries from continued erosion of coastal permafrost in Eurasia (*Shakova et al., 2005*), and over centuries to millennia from the propagation of any warming 100 to 1,000 meters down into permafrost hydrates (*Harvey and Huang, 1995*).

7.3. Changes in Wetland Extent and Methane Productivity

Although a destabilization of either the marine or terrestrial methane hydrate reservoirs is the most likely pathway for an abrupt increase in atmospheric methane concentration, the potential exists for a more gradual, but substantial, increase in natural methane emissions in association with projected changes in climate. The most likely region to experience a dramatic change in natural methane emission is the northern high latitudes, where there is increasing evidence for accelerated warming, enhanced precipitation, and widespread permafrost thaw which could lead to an expansion of wetland areas into organic-rich soils that, given the right environmental conditions, would be fertile areas for methane production (*Jorgenson et al., 2001, 2006*).

Tropical wetlands are a stronger methane source than boreal/arctic wetlands, and will likely continue to be over the next century, during which fluxes from both regions are expected to increase. However, several factors that differentiate northern wetlands from tropical wetlands make them more likely to experience a larger increase in fluxes.

The balance of evidence suggests that anticipated changes to northern wetlands in response to large-scale permafrost degradation, thermokarst development, a positive trend in water balance in combination with substantial soil warming, enhanced vegetation productivity, and an abundant source of organic matter will very likely drive a sustained increase in CH_4 emissions from the northern latitudes during the 21st century. A doubling of CH_4 emissions could be realized fairly easily. Much larger increases cannot be discounted.

Summary

The prospect of a catastrophic release of methane to the atmosphere as a result of anthropogenic climate change appears very unlikely. However, the carbon stored as methane hydrate and as potential methane in the organic carbon pool of northern (and tropical) wetland soils is likely to play a role in future climate change. Changes in climate, including warmer temperatures and more precipitation in some regions, will very likely gradually increase emission of methane from both melting hydrates and natural wetlands. The magnitude of this effect cannot be predicted with great accuracy yet, but is likely to be at least equivalent to the current magnitude of many anthropogenic sources.

Box 1.1—Treatment of Uncertainties in the SAP 3.4 Assessment

This report follows the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (*IPCC, 2007*) in the treatment of uncertainty, whereby the following standard terms are used to define the likelihood of an outcome or result where this can be estimated probabilistically based on expert judgment about the state of that knowledge:

Likelihood terminology	Likelihood of occurrence/outcome
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Extremely unlikely	<5% probability
Exceptionally unlikely	<1% probability

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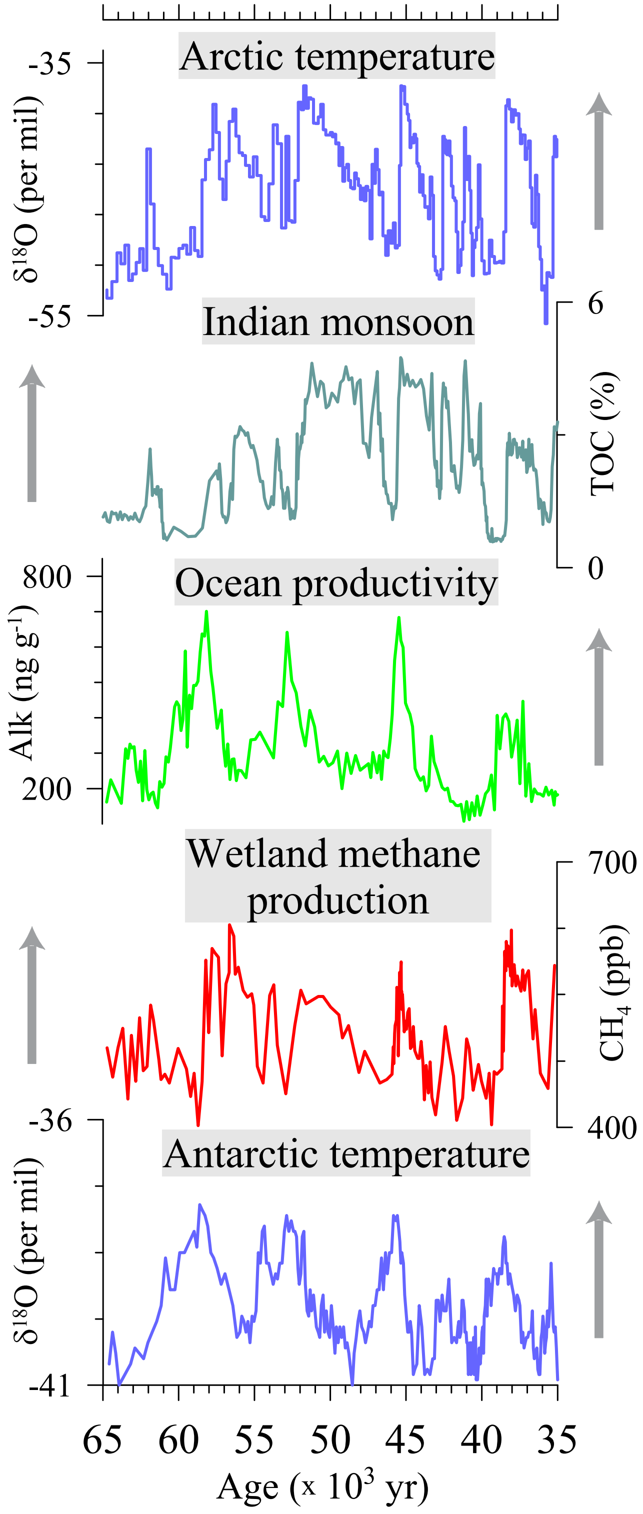

Figure 1.1. Records of climate change from the time period 35,000 to 65,000 years ago, illustrating how many aspects of the Earth's climate system have changed abruptly in the past. In all panels, the upward-directed gray arrows indicate the direction of increase in the climate variable recorded in these geologic archives (i.e., increase in temperature,

increase in monsoon strength, etc.). The upper panel shows changes in the oxygen-isotopic composition of ice ($\delta^{18}O$) from the GISP2 Greenland ice core (*Grootes et al., 1993*). Isotopic variations record changes in temperature of the high northern latitudes, with intervals of cold climate (more negative values) abruptly switching to intervals of warm climate (more positive values), representing temperature increases of $8^{o}C$ to $15^{o}C$ typically occurring within decades (*Huber et al., 2006*). The next panel down shows a record of strength of the Indian monsoon, with increasing values of total organic content (TOC) indicating an increase in monsoon strength (*Schulz et al., 1998*). This record indicates that changes in monsoon strength occurred at the same time as, and at similar rates as, changes in high northern-latitude temperatures. The next panel down shows a record of the biological productivity of the surface waters in the southwest Pacific Ocean east of New Zealand, as recorded by the concentration of alkenones in marine sediments (*Sachs and Anderson, 2005*). This record indicates that large increases in biological productivity of these surface waters occurred at the same time as cold temperatures in high-northern latitudes and weakened Indian monsoon strength. The next panel down is a record of changes in the concentration of atmospheric methane (CH_4) from the GISP2 ice core (*Brook et al., 1996*). As discussed in Chapter 5 of this report, methane is a powerful greenhouse gas, but the variations recorded were not large enough to have a significant effect on radiative forcing. However, these variations are important in that they are thought to reflect changes in the tropical water balance that controls the distribution of methane-producing wetlands. Times of high-atmospheric methane concentrations would thus correspond to a greater distribution of wetlands, which generally correspond to warm high northern latitudes and a stronger Indian monsoon. The bottom panel is an oxygen-isotopic ($\delta^{18}O$) record of air temperature changes over the Antarctic continent (*Blunier and Brook, 2001*). In this case, warm temperatures over Antarctica correspond to cold high northern latitudes, weakened Indian monsoon and drier tropics, and great biological productivity of the southwestern Pacific Ocean.

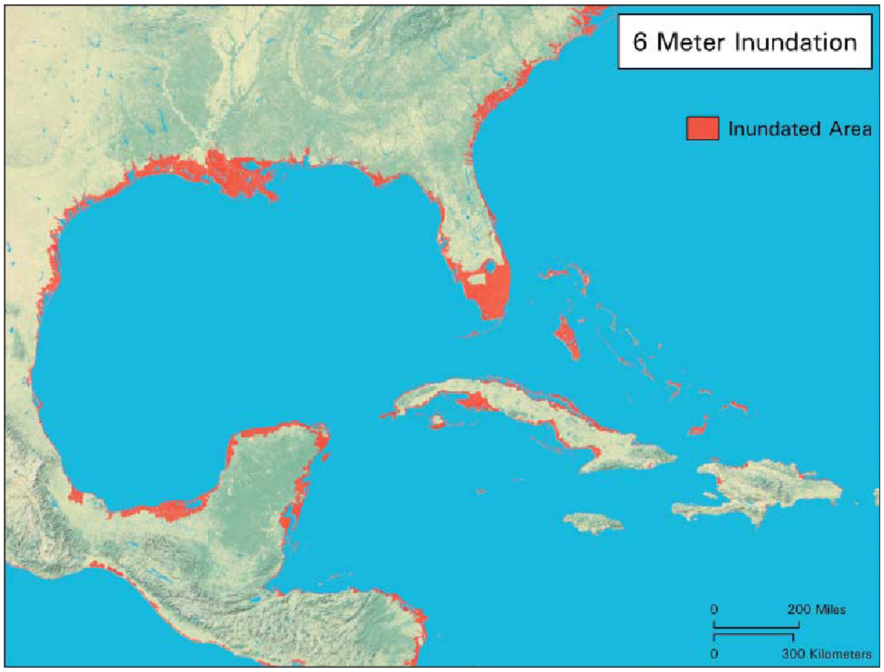

Figure 1.2. Portions (shown in red) of the southeastern United States, Central America, and the Caribbean that would be inundated by a 6-meter sea level rise (from *Rowley et al., 2007*).

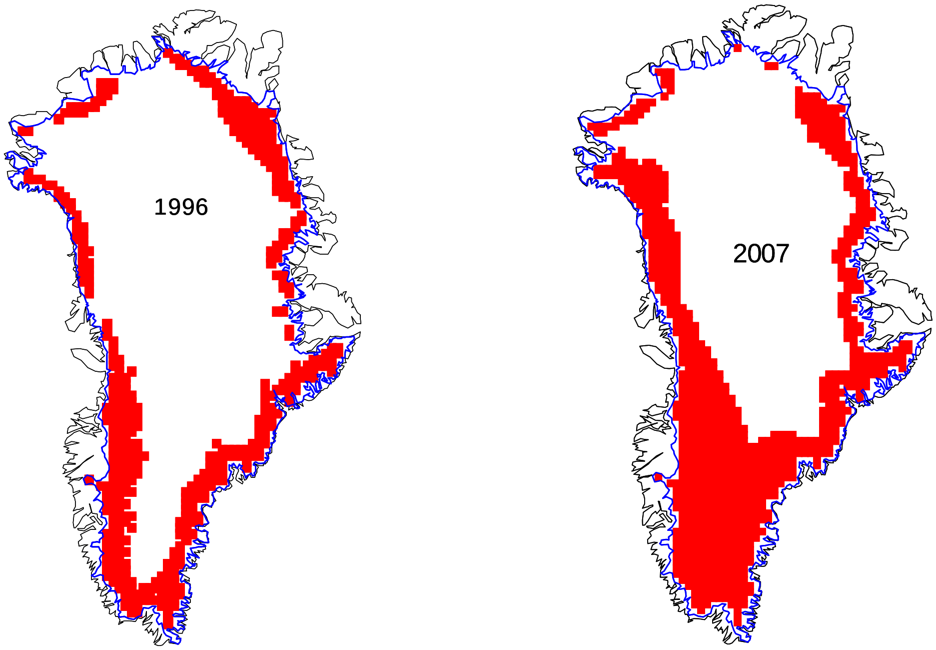

Figure 1.3. The map shows the average number of melt days from 1979 to 1996 (left) and 1979-2007 (right) at each passive microwave pixel on the ice sheet. The lower graph shows the total area experiencing melt during each annual melt cycle summed from April

1 through October 31. Error bars represent the 95% confidence interval (from K. Steffen, CIRES, University of Colorado).

Figure 1.4. Photograph showing a dust storm approaching Stratford, Texas, during the 1930's Dust Bowl. (NOAA Photo Library, Historic NWS collection).

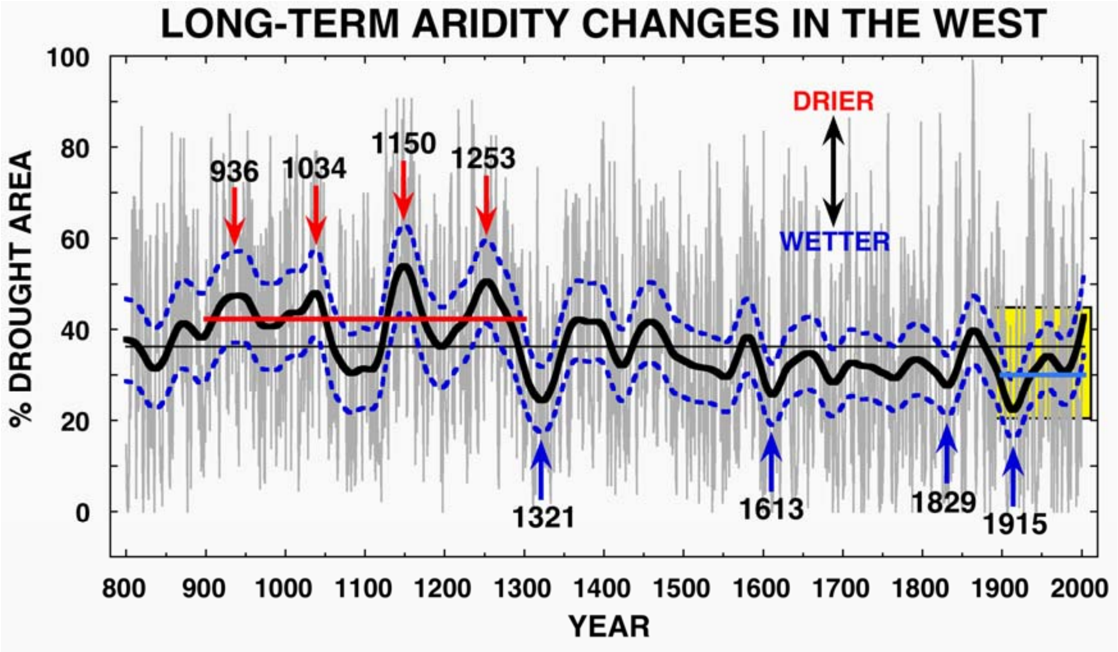

Figure 1.5. Percent area affected by drought (PDSI<-1) in the area defined as the West (see Chapter 3 of this report) (from *Cook et al., 2004*). Annual data are in gray and a 60-year low-pass filtered version is indicated by the thick smooth curve. Dashed blue lines are 2-tailed 95% confidence limits based on bootstrap resampling. The modern (mostly 20th century) era is highlighted in yellow for comparison to an increase in aridity prior to about A.D. 1300.

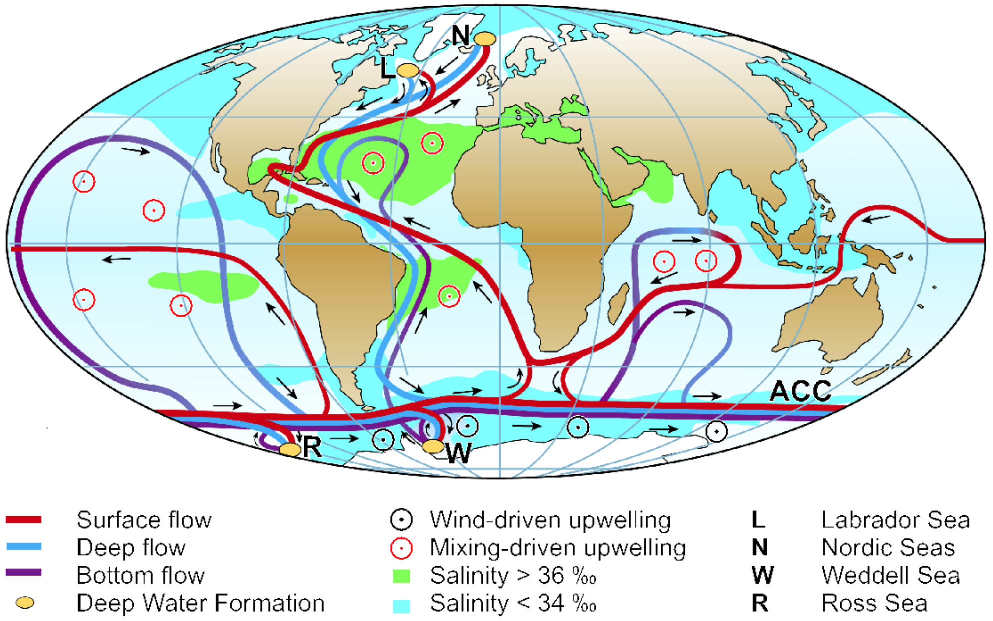

Figure 1.6. Schematic of the ocean circulation (from *Kuhlbrodt et al., 2007*) associated with the global Meridional Overturning Circulation (MOC), with special focus on the Atlantic section of the flow (AMOC). The red curves in the Atlantic indicate the northward flow of water in the upper layers. The filled orange circles in the Nordic and Labrador Seas indicate regions where near-surface water cools and becomes denser, causing the water to sink to deeper layers of the Atlantic. The light blue curve denotes the southward flow of cold water at depth. See Chapter 4 of this report for further explanation.

Figure 1.7. Palm trees on Mullaghmore Head, County Sligo, Ireland, which are symbolic of the relatively balmy climates of Ireland provided in part by the heat supplied from the Atlantic Meridional Overturning Circulation. (Reprinted with permission from http://www.a-wee-bit-of-ireland.com, copyright 2004).

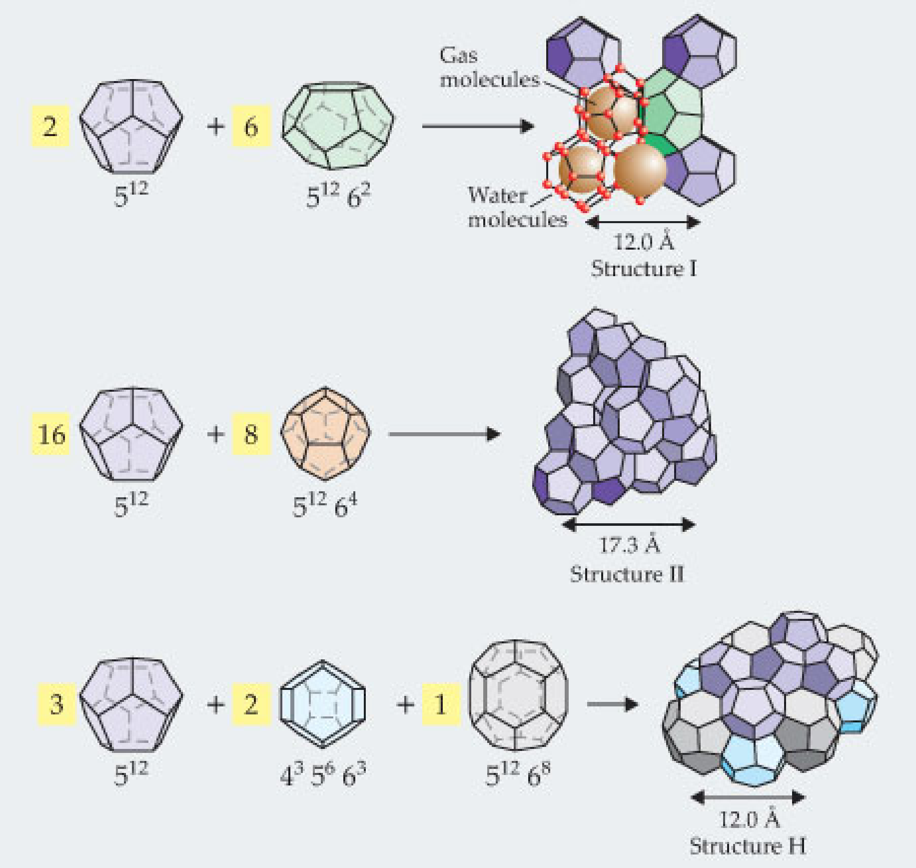

Figure 1.8. Clathrate hydrates are inclusion compounds in which a hydrogen-bonded water framework—the host lattice—traps "guest" molecules (typically gases) within ice cages. The gas and water don't chemically bond, but interact through weak van der Waals forces, with each gas molecule—or cluster of molecules in some cases—confined to a single cage. Clathrates typically crystallize into one of the three main structures illustrated here. As an example, structure I is composed of two types of cages: dodecahedra, 20 water molecules arranged to form 12 pentagonal faces (designated 5^{12}), and tetrakaidecahedra, 24 water molecules that form 12 pentagonal faces and two hexagonal ones ($5^{12}6^{2}$). Two 5^{12} cages and six $5^{12}6^{2}$ cages combine to form the unit cell. The pictured structure I illustrates the water framework and trapped gas molecules (from *Mao et al., 2007*). See Chapter 5 of this report for further explanation.

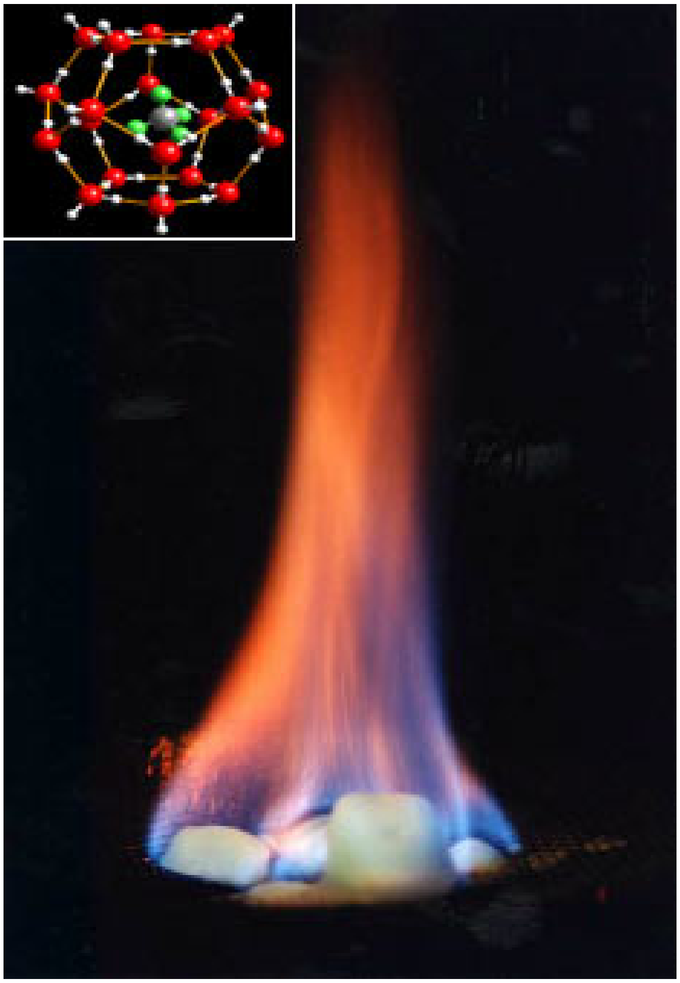

Figure 1.9. A piece of methane clathrate displays its potential as an energy source. As the compound melts, released gas feeds the flame and the ice framework drips off as liquid water. Inlay shows the clathrate structure. Source: U.S. Geological Survey.