Abrupt Climate Change

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Science **299**, 2005 (2003);
DOI: 10.1126/science.1081056

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.

Abrupt Climate Change

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Large, abrupt, and widespread climate changes with major impacts have occurred repeatedly in the past, when the Earth system was forced across thresholds. Although abrupt climate changes can occur for many reasons, it is conceivable that human forcing of climate change is increasing the probability of large, abrupt events. Were such an event to recur, the economic and ecological impacts could be large and potentially serious. Unpredictability exhibited near climate thresholds in simple models shows that some uncertainty will always be associated with projections. In light of these uncertainties, policy-makers should consider expanding research into abrupt climate change, improving monitoring systems, and taking actions designed to enhance the adaptability and resilience of ecosystems and economies.

Climatic records show that large, widespread, abrupt climate changes have occurred repeatedly throughout the geological record. Some mechanisms have been identified that could account for these changes, and model simulations of them are improving, but the models that are currently being used to assess human impacts on climate do not yet simulate the past changes with great accuracy. Although public debate regarding climate change has focused on the climatic consequences of greenhouse-gas emissions and their impacts on the planet and on human societies, scientists and policy-makers have given less attention to the possibility that large climate changes could occur quickly. Such abrupt climate changes could have natural causes, or could be triggered by humans and be among the "dangerous anthropogenic interferences" referred to in the U.N. Framework Convention on Climate Change (FCCC) (*1*). Thus, abrupt climate change is relevant to, but broader than, the FCCC and consequently requires a broader scientific and policy foundation. Here we describe the scientific foundation for a research agenda focused on abrupt climate change, as developed in a recent study by an international panel of the U.S. National Research Council (*2*), and identify areas in which the possibility of abrupt climate change has a bearing on the current policy debate about human-induced climate change.

What Climate Has Done

Long-term stabilizing feedbacks have maintained Earth-surface conditions within the narrow liquid-water window conducive to life for about 4 billion years (*3*); however, data indicate that over times of 1 year to 1 million years, the dominant feedbacks in the climate system have amplified climate perturbations. For example, global-mean temperature changes of perhaps 5° to 6°C over ice-age cycles (*4*) are generally believed to have resulted from small, globally averaged net forcing (*5*). More surprisingly, regional changes over ~10 years without major external forcing were in many cases one-third to one-half as large as changes over the ~100,000-year ice-age cycles (*4*, *6*).

"Technically, an abrupt climate change occurs 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" (*2*, p. 14). Even a slow forcing can trigger an abrupt change, and the forcing may be chaotic and thus undetectably small. For human concerns, attention is especially focused on persistent changes that affect subcontinental or larger regions, and for which ecosystems and economies are unprepared or are incapable of adapting.

Instrumental records reveal detailed, global information on abrupt, often societally disruptive, climate shifts. For example, the warming that occurred during the 20th century in many northern regions was concentrated in two rapid steps, suggestive of a juxtaposition of human-induced secular trend and interdecadal variability due to natural causes (*7*). The warming on the Atlantic side of the Arctic during the 1920s was 4°C or more in places (*8*) (Fig. 1). During the following decade, an extended drought often called the Dust Bowl had a lasting impact on the United States (*9*, *10*). Such abrupt-onset, severe regional drought regimes have been infrequent in the United States during the instrumental period but more common elsewhere, including in the Sahel (*11*). The strong links in many regions between drought or flood and the El Niño–Southern Oscillation (ENSO) system (*12*) focus attention on ENSO regime shifts (*13*).

An abrupt Pacific shift in 1976–1977, perhaps related to ENSO, involved enhancement of the dominant pattern of atmospheric circulation (including a deepening of the Aleutian Low), an oceanwide change of surface temperature (warmer in the tropics and along the coast of the Americas, colder to the west at temperate latitudes) (*14*), and warming-induced shifts in ecosystems along the coast of the Americas (*15*). On the Atlantic side, the past 30 years have witnessed an invasion of low-salinity deep waters that spread over the entire subpolar North Atlantic Ocean and the seas between Greenland and Europe (*16*) in just the regions critical for abrupt shifts in the thermohaline circulation, which has been implicated in many abrupt climate-change events of the past (see below).

The instrumental record is becoming more valuable as it is lengthened, but is insufficient to have sampled the full range of climatic behavior. Paleoclimatic records from the Holocene (the current, 10,000-year interglacial warm period) show larger abrupt changes in regional climate than recorded instrumentally. These include apparently abrupt shifts in past hurricane frequency (*17*), changes in flood regimes, and especially prominent droughts (*10*) (Fig. 2). Examples include episodic desiccation of lakes in African (*18*) and Asian (*19*) monsoonal areas, remobilization of dunes on the U.S. high plains, the multidecadal drought implicated in

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the collapse of classic Mayan civilization (*20*), and the multicentennial drought associated with the fall of the Akkadian empire (*21*). Shifts in drought regimes appear to have often been abrupt (*10*).

Many paleoclimatic records, and especially those from high latitudes, show that ice-age events were even larger and more widespread than those of the Holocene or of previous interglacials (*6*). Regional climate changes of as much as 8° to 16°C (*6*, *22*) occurred repeatedly in as little as a decade or less (Fig. 3). The data do not yet exist to draw quantitatively reliable, global anomaly maps of any major climate variables for these changes, but effects were clearly hemispheric to global (*4*) and included changes in tropical wetlands (*23*) and the Asian monsoon (*24*). Cold, dry, and windy conditions generally occurred together, although antiphase behavior occurred in parts of the Southern Ocean and Antarctica (*6*). These jumps associated with the Dansgaard-Oeschger (DO) oscillation (*25*) were especially prominent during the cooling into and warming out of ice ages, but persisted into the early part of the current Holocene warm period (Fig. 3).

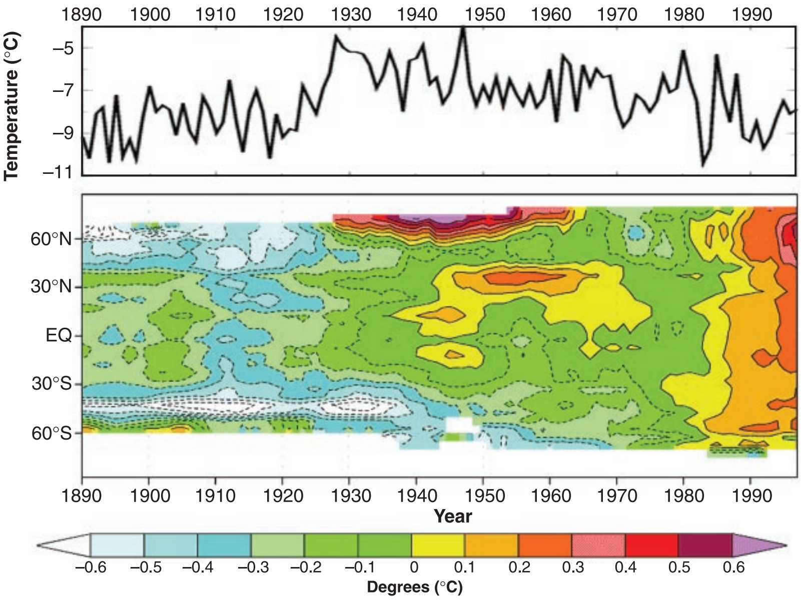

Fig. 1. Observed, zonally averaged, land-surface air-temperature anomalies (°C) as a function of latitude and time (*7*), together with the temperature record for the same interval from Upernavik, Greenland (72°47′N, 56°10′W, on the northwest coast of Greenland) (*8*). Global instrumental coverage is just sufficient to capture the rapid, concentrated warming at high northern latitudes in the 1920s, which is shown more dramatically at sites such as Upernavik.

Why Climate Changed Abruptly

Systems exhibiting threshold behavior are familiar. For example, leaning slightly over the side of a canoe will cause only a small tilt, but leaning slightly more may roll you and the craft into the lake. Such large and rapid threshold transitions between distinct states are exhibited by many climate models, including simplified models of the oceanic thermohaline circulation (*26*), atmospheric energy-balance models (*27*), and atmospheric dynamical models exhibiting spontaneous regime changes (*28*).

An abrupt change, of a canoe or the climate, requires a trigger, such as you leaning out of a canoe; an amplifier and globalizer, such as the friction between you and the canoe that causes the boat to flip with you; and a source of persistence, such as the resistance of the upside-down canoe to being flipped back over.

Many triggers have been identified in the climate system. For example, the drying of the Sahara during the latter part of the Holocene, and the ice-age DO oscillations, are linked in time and mechanistically to orbital forcing. The Sahara dried as the African monsoon weakened in response to reduction in summertime incoming solar radiation (*29*). The DO oscillations were especially prominent during the orbitally mediated cooling into and warming out of the ice age. Triggers may be fast (e.g., outburst floods from glacier-dammed lakes), slow (continental drift, orbital forcing), or somewhere between (human-produced greenhouse gases), and may even be chaotic; multiple triggers also may contribute.

Amplifiers are abundant in the climate system and can produce large changes with minimal forcing. For example, drying causing vegetation dormancy or death reduces the evapotranspiration that supplies moisture for a sizable fraction of the precipitation in many continental regions, further reducing rainfall and reinforcing drought (*29*). In cold regions, cooling increases surface coverage by snow and ice, increasing reflection of incoming solar radiation and causing even further cooling in an ice-albedo feedback.

These positive feedbacks may include their own sources of persistence. Loss of vegetation reduces the ability of roots to capture water and allows subsequent precipitation to run off to streams and the oceans, perhaps leading to desertification (*30*). If snowfall on land persists long enough, an ice sheet may grow sufficiently thick that its surface becomes high enough and cold enough that melting is unlikely. Persistence also may arise from the wind-driven circulation of the oceans, stratospheric circulation and related chemistry (*31*), or other processes.

For the DO oscillations, the thermohaline circulation of the oceans is implicated in the persistence. In the presently most likely hypothesis, warm, salty water flowing into the North Atlantic densifies as it cools and then sinks. However, precipitation and runoff from surrounding land masses supply more fresh water to the North Atlantic than is removed by evaporation. Failure of sinking would allow freshening to decrease surface density, preventing further sinking and the associated inflow of warm waters [e.g. (*4*, *6*)].

Whereas triggers, amplifiers, and sources of persistence are easily identified, globalizers that spread anomalies across large regions or even the whole Earth are less obvious. General circulation models (GCMs) forced by hypothesized causes of abrupt climate changes often simulate some regional changes rather well, underestimate others, and fail to generate sufficiently widespread anomaly patterns [e.g. (*2*, *29*, *32*, *33*)]. The high quality and numerous cross-checks in at least some paleoclimatic data sets indicate that the data-model mismatch is unlikely to result from misinterpretation of the data. Either some natural forcings have been omitted from the numerical experiments, or the

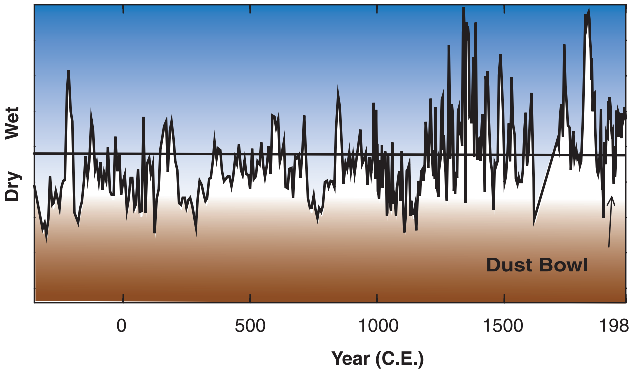

Fig. 2. Salinity of Moon Lake, North Dakota, USA (46°51′27″N, 98°09′30″W) derived from diatom records (*71*). The Dust Bowl drought of the 1930s is shown clearly by increased lake salinity, but larger and longer droughts, often with abrupt onsets, occurred frequently before ~1200.

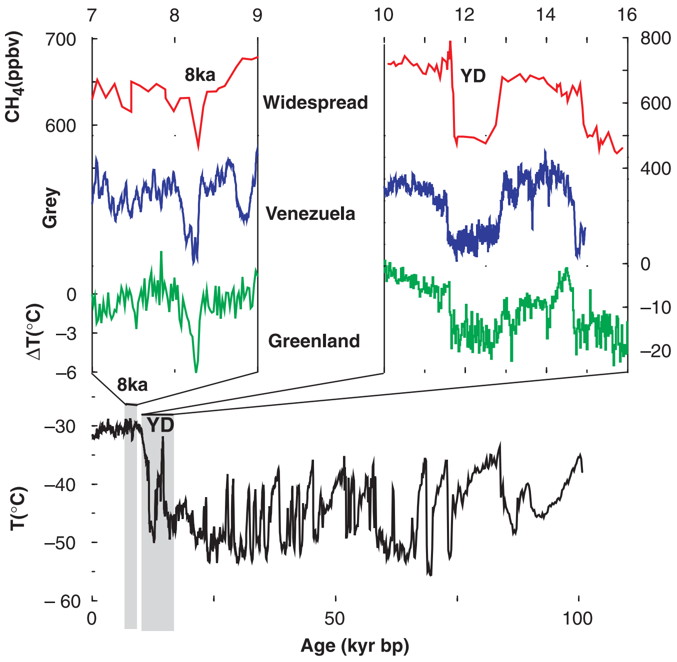

Fig. 3. Paleoclimatic data showing abrupt climate changes, after (*45*) and other sources. The lower panel is the history of temperature in central Greenland over the last 110,000 years (*72*). Details of temperature for the Younger Dryas (YD) event and for the cold event about 8200 years ago (8ka) are shown as deviations from the temperature averaged over the intervals from 7000 to 8000 and 8400 to 9000 years ago. Methane concentrations (*23*) reflect production in global wetlands, including important tropical sources. Gray-scale of a sediment core from the Cariaco Basin, offshore Venezuela (*73*), is plotted here so that a downward shift corresponds to the effects of stronger winds over the basin or decreased rainfall on adjacent land. Note differences in scales in the detailed figures; the scale for the Cariaco Basin record is not shown, but has twice the range for the YD as for the 8ka.

GCMs used in these experiments have tended to underestimate the size and extent of climate response to threshold crossings (*34*).

There is no shortage of hypotheses to explain model underestimation of abrupt climate changes. In considering DO oscillations, for example, if the trigger were in the tropics or elsewhere with the North Atlantic serving only as an amplifier and source of persistence, then errors might be expected from models testing only North Atlantic triggers. Strong evidence for such tropical or other triggers is still lacking, however.

Attention has recently focused on the possibility of solar forcing contributing to abrupt climate change. Moderate climate oscillations during the Holocene, such as the Little Ice Age, exhibit somewhat the same spacing in time as the higher amplitude DO oscillations (*35*, *36*), and the Holocene oscillations may be linked to solar forcing (*35*). It has been hypothesized that the DO oscillations were caused by interaction between a weak solar periodicity and noise in the climate system linked at least in part to North Atlantic processes (*37*).

Interdecadal climate change is greatly influenced by preferred modes of variability of the climate system, and especially by the ENSO and the southern and northern annular modes (*38*). Strong evidence links regional abrupt climate changes to shifts in preferred modes, such as dependence of droughts and floods on ENSO processes (*13*), or dependence of large Arctic changes on trends in the northern annular mode (*16*, *38*). The prominence of such climate-mode shifts in recent climate changes suggests an important role further in the past, and in the future. Better representation of modes in climate models thus may improve simulations of abrupt climate changes.

Other model improvements also may help in simulating abrupt climate change. Using a simple Stommel (*26*)–type box model of the ocean circulation, Marotzke (*39*) found abrupt shifts between qualitatively different, persistent states akin to those implicated in the DO oscillation; however, progressively increasing the strength of mixing processes weakened and then removed this behavior (Fig. 4). Observations have recently indicated a complex spatial structure of mixing in the oceans (*40*); however, GCMs often have represented these complex processes simply as uniform, strong mixing, which may have contributed to reduced model sensitivity to threshold crossings compared to observed responses.

Impacts of Abrupt Climate Change on Ecological and Economic Systems

Although there is a substantial body of research on the ecological and societal impacts of climate change, virtually all research has relied on scenarios with slow and gradual changes [e.g. (*41*)]. In part, this focus reflects how recently the existence of abrupt climate changes gained widespread recognition, and how difficult it has been to generate appropriate scenarios of abrupt climate change for impacts assessments. In addition, the FCCC (*1*) has focused attention on anthropogenic forcing, whereas abrupt climate change is a broader subject covering natural as well as human causes.

Most ecological and economic systems have the ability to adapt to a changing environment. Slower changes allow response with less disruption in both ecosystems and economies [e.g. (*42*)]. Abrupt changes are particularly harmful where the individual entities have long lifetimes or are relatively immobile; damages also increase with the abruptness and unpredictability of the climate change and are likely to be larger if the system is unmanaged. Long-lived and relatively immobile unmanaged ecosystems such as mature forests and coral reefs thus are likely to be especially sensitive to climate change, and specific attention to vulnerable sectors such as these is warranted.

In the ecological sphere, biological records (pollen, macrofossils) in sediment are useful in reconstructing abrupt climate changes because their effects often were so large [e.g. (*43*)]. Local extinctions and extensive ecosystem disruptions occurred in regions including the northeastern and central-Appalachian United States in fewer than 50

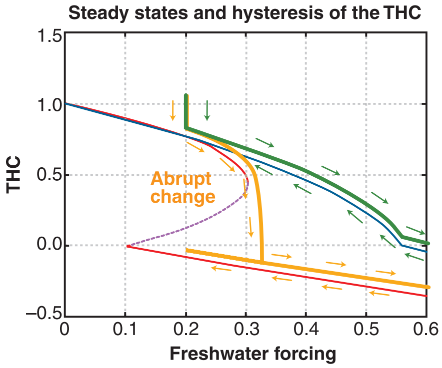

Fig. 4. Results from a very simple, conceptual model of the Atlantic thermohaline circulation (THC), building on Stommel (*2*, *26*). The blue and red curves show steady-state THC strength as a function of the freshwater loss to the atmosphere in the subtropics (equal to freshwater gain at high latitudes). The red (blue) curve shows the case for weak (strong) mixing, which here represents either true oceanic mixing or processes such as the wind-driven circulation that are not modeled explicitly. Orange (green) curves and arrows show the responses of the models with weak (strong) mixing to a slow increase and subsequent decrease in freshwater forcing, starting from 0.2 in arbitrary units. Only in the case of weak diffusion (orange) does the model respond with an abrupt change, once a threshold in freshwater forcing is crossed. This model does not return to its original state after the anomalous forcing has gone back to zero (hysteresis behavior). In the case of strong diffusion (green), at any time, there is a unique equilibrium. It is not currently possible to establish whether the real Atlantic THC is better represented qualitatively by the red/orange or by the blue/green curves. This analysis also suggests that during the early stages of freshwater-forcing increase, THC observations cannot distinguish between the two possible cases.

years following the end of the Younger Dryas cold event (*43*), which was a prominent return to colder conditions during the most recent deglaciation, with an abrupt onset and especially abrupt termination, probably linked to the DO oscillations (*6*) (Fig. 3). Large ecosystem shifts required fewer than 20 years in central Europe during the abrupt cooling about 8200 years ago (*44*). During this event, fallout of materials from upwind fires became more frequent in central Greenland almost synchronously with climate changes, reflecting rapid response probably in North America (*45*).

The extinctions of numerous large North American mammals occurred very close in time to the abrupt shift into the Younger Dryas. The climate change is unlikely to have been solely responsible, because the fauna previously survived many similar shifts. However, stress from abrupt climate change may have combined with human hunting pressure to cause the extinctions (*46*). Similarly, while extant biota have survived previous abrupt climate changes through extensive and rapid migrations, human-caused habitat fragmentation and other anthropogenic influences may impede migrations and thereby increase vulnerability of certain ecological systems to any future abrupt climate changes (*47*, *48*). Major and abrupt changes in fisheries and other ecosystems have been caused by climate shifts during the 20th century, such as the North Atlantic warming during the 1920s or the ENSO regime shift during the 1970s (*13*, *49*). Sensitive regions such as coastal oceans may have been especially impacted, with effects on the occurrence and abundance of diseases (*50*).

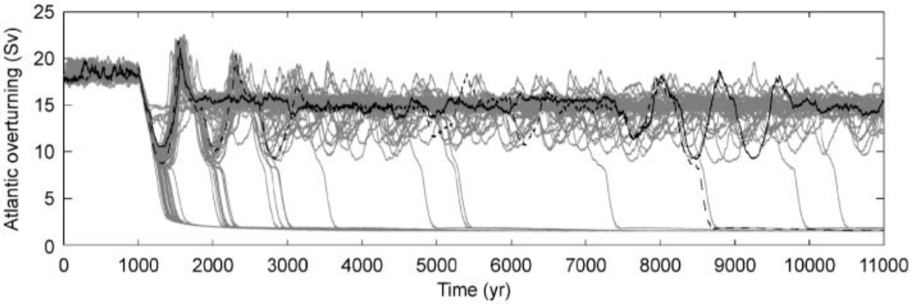

Fig. 5. Evolution of the maximum overturning in the Atlantic [strength of the THC given in Sverdrups (Sv); 1 Sv = 10^6 m^3/s] for a coupled model of reduced complexity for 100 model realizations. Radiative forcing is increased from years 1000 to 1140, equivalent to a doubling of CO_2, and then held constant. The warming pushes the model closer to the bifurcation point, and transitions usually occur when the overturning is weakened. Two individual realizations are highlighted by the black lines, one in which the THC remains strong but highly variable, and one in which the THC undergoes a rapid transition much later than, and completely unrelated in time to, the forcing. Transitions occur preferentially following a notable reduction of the THC, suggesting the possibility for an early indicator (*63*).

Economic studies indicate that many sectors of the economy can adapt to gradual climate changes over the coming decades. But this research sheds little light on the impacts of abrupt climate changes, particularly where these involve major changes in precipitation and water availability over periods as short as a decade. Among produced capital stocks, buildings and infrastructure specific to particular locations and adapted to particular climates, with lifetimes of 50 to 100 years, are especially vulnerable to abrupt climate changes. For shorter lived or more-mobile capital stocks such as computers or health-care facilities, gradual climate change over decades may have only small economic impacts, but abrupt climate change might have larger impacts (*51*). The few available studies comparing no-adaptation to adaptation strategies indicate that faster and less-anticipated climate changes are much more costly (*52*, *53*).

Research coupling economic and climate models has progressed over the past decade, but there is virtually no linked research on abrupt climate change. For gradual climate change, economic estimates indicate that efficient economic response involves modest but increasing emissions reductions and carbon taxes to slow climate change (*51*). However, efficiently avoiding abrupt change may involve much larger abatement costs (*54*).

Outlook

Past abrupt changes were especially prominent while the climate was being forced to change from one state to another. This is consistent with models showing that forcing increases the probability of a threshold crossing. If human activities are driving the climate system toward one of these thresholds, it will increase the likelihood of an abrupt climate change in the next hundred years or beyond (*55*).

Thresholds may exist in many parts of the climate system. Model projections of global warming often include increased global precipitation, enhanced variability in precipitation, and summertime drying in many continental interiors, including "grain belt" regions (*49*, *56*). We may see simultaneously both gradual and abrupt increases in floods and droughts. Abrupt changes are possible in ice sheets affecting sea level and ocean circulation, in permafrost affecting land-surface processes and greenhouse-gas fluxes, and in sea ice and other parts of the climate system. Shifts in the coupled modes, such as ENSO (*13*) or the annular modes (*31*), may be important. One cannot exclude the possibility of abrupt change to warm-climate modes that have not been visited recently but may have occurred further back in time (*57*).

For the ice-age events, surface freshening of the North Atlantic is implicated in abrupt coolings, with return of salty waters tied to abrupt warmings [e.g. (*4*)]. Many models of global warming project future North Atlantic freshening from increased precipitation and runoff (*56*), increasing buoyancy of surface waters and slowing the thermohaline circulation, consistent with recently observed trends (*16*, *58*). The likely impacts have not been studied carefully but may be substantial (*54*, *59*). In contrast, global-warming results from one model (*60*) showed changes in ENSO frequency and amplitude that increased Atlantic salinity, compensating for enhanced high-latitude precipitation to maintain a vigorous thermohaline circulation. This finding emphasizes the potential role of mode changes in natural climate variability, as well as associated stabilizing feedbacks that are poorly understood.

Not only the magnitude, but also the rates of human forcing of the climate system, are crucial issues for abrupt climate change. For example, model results indicate that faster warming would weaken the thermohaline circulation more by producing stronger vertical density gradients opposing sinking in the North Atlantic (*61*). Both faster warming and weakening of the thermohaline flow (*62*) render the thermohaline circulation less stable against perturbations by moving closer to thresholds. Very close to a threshold, the thermohaline circulation may lose predictability, as shown by recent model simulations (Fig. 5) (*63*). Thus, although the climate around the North Atlantic and in many other regions has been more stable during the warmer Holocene than during the ice age, additional, rapid global warming could serve to increase the likelihood of large, abrupt, persistent, and to some extent unpredictable, changes.

On the basis of current understanding, events such as the collapse of the West Antarctic ice sheet (*56*) or a switch to some unanticipated warm climate mode (*57*) are considered to have low probability, but if they occurred rapidly, they would have large and damaging impacts. Improved understanding of the full range of possible abrupt climate changes, through sustained collection and study of instrumental and paleoclimatic data, improved statistical techniques, simulations with a hierarchy of models, and impacts assessments, could be of considerable value to policy-makers seeking to promulgate effective responses (*2*).

The difficulty of identifying and quantifying all possible causes of abrupt climate change, and the lack of predictability near thresholds, imply that abrupt climate change will always be accompanied by more uncertainty than will gradual climate change. Given the deep uncertainty about the nature and speed of future climate changes, policy-making thus might focus on reducing vulnerability of systems to impacts by enhancing ecological and societal resiliency and adaptability. Failure of the Viking settlements in Greenland but persistence of the neighboring Inuit during Little Ice Age cooling [e.g. (*64*)] underscores the value of developing effective strategies that are favorable in the face of unanticipated abrupt climate change. Research that contributes to identification and evaluation of "no-regrets" policies—those actions that are otherwise sensible and will improve resiliency and adaptability—may be especially useful (*2*). Slowing the rate of human forcing of the climate system may delay or even avoid crossing of thresholds (*61*).

Overall, instrumental and paleoclimatic data indicate that large, rapid, widespread climate changes with persistent impacts have occurred repeatedly in the past. Although they probably had the largest effects on land-surface moisture and high-latitude temperatures, the climatic effects were often global. Simple models confirm the possibility of future abrupt climate changes and suggest that the rapid increase in human-induced forcings increases the probability of crossing a threshold and triggering an abrupt climate change. The methodology used by the Intergovernmental Panel on Climate Change (IPCC) (*56*) to project the future has emphasized the use of complex atmospheric models with simplified representations of other elements of the climate system to simulate the forced response to increasing concentrations of greenhouse gases over the course of the next century. Such climate models are improving rapidly but have not yet reached the level of sophistication that will enable them to be used to simulate the likelihood of occurrence of the more abrupt and possibly spontaneous climate shifts described in this paper.

Any future abrupt climate change might have large and unanticipated impacts. Improved understanding of the processes may increase the lead time for mitigation and adaptation. More-precise estimates of impacts of abrupt climate change could make response strategies more effective. The persistence of some uncertainty regarding future abrupt climate changes argues in favor of actions to improve resiliency and adaptability in economies and ecosystems. Much fruitful work remains to be done to improve our understanding of the history, mechanisms, policy, and social implications of abrupt climate change.

References and Notes

1. The United Nations Framework Convention on Climate Change can be viewed at http://unfccc.int/resource/conv/index.html.
2. The National Research Council (NRC) report *Abrupt Climate Change: Inevitable Surprises* (*65*) provides a more comprehensive treatment of abrupt climate change, with over 650 references. The members of the Panel on Abrupt Climate Change, which prepared the NRC report, are the authors of this review. The recommendations of the NRC report: Improve the fundamental knowledge base, modeling, instrumental and paleoclimatic data, and statistical approaches related to abrupt climate change, and investigate "no-regrets" strategies to reduce vulnerability. The report is available at http://books.nap.edu/books/0309074347/html/1.html#pagetop.
3. Short-term climate stability is provided by the increase in longwave radiation emitted by Earth as it warms, and reduction in emitted radiation as it cools. The large heat capacity and specific heats of water also contribute to very short term stability. Very long term stability likely occurs because the rate of production of CO$_2$ from volcanoes is nearly independent of Earth's surface temperature, but the rate at which CO$_2$ is removed from the atmosphere by chemical reaction with rocks increases with temperature, which increases with atmospheric CO$_2$ (*66*).
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58. Freshening may be arising from one or more processes, including increased high-latitude precipitation or fraction of precipitation running off the land (*69*), melting of sea or land ice, or changes in wind-driven or other exchange with the Arctic Ocean; the complexity is challenging for modern observations and models (*16*).
59. Seager *et al.* (*70*) emphasized that the relative warmth of the northeastern versus northwestern Atlantic arises only in part from the thermohaline circulation; thus, any discussions of the possible effects of a thermohaline shutdown that cite the Norway-Canada difference may be overstated. Nonetheless, the thermohaline circulation does transport much heat to, and affect the climate of, the North Atlantic (*4*, *70*). The tendency of many models to underestimate abrupt paleoclimatic changes leaves open the possibility that other discussions have underestimated the potential effects of a thermohaline shutdown. The need for improved research to address these issues is clear.
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74. We thank NRC staff (A. Isern, J. Dandelski, C. Elfring, M. Gopnik, M. Kelly, J. Bachim, A. Carlisle), the U.S. Global Change Research Program and the Yale National Bureau of Economic Research on International Environmental Economics for study funding, sponsors of our research (including NSF OPP 0087160 to R.B.A.), the community of researchers studying abrupt climate change who made this possible, and especially D. Bradford, W. Curry, and K. Keller for helpful comments.