Abrupt Climate Change


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 and the El Nino–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 in 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 dunies on the U.S. high plains, the multidecadal drought implicated in
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).

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 vegetation, and 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
important tropical sources. Gray-scale of a sediment core from the 
intervals from 7000 to 8000 and 8400 to 9000 years ago. Methane 
Greenland over the last 110,000 years (\cite{other sources}. The lower panel is the history of temperature in central 
mate response to threshold crossings (\cite{GCMs used in these experiments have tended to 
noise in the climate system linked at least 
attitude DO oscillations (\cite{oscillations during the Holocene, such as 
other triggers is still lacking, however. 
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 (\cite{44}). 
There is no shortage of hypotheses to 
explain model underestimation of abrupt cli- 
mate changes. In considering DO oscilla- 
tions, 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 trig-
ners. 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 
space in time as the higher amplitude DO oscilla-
tions (\cite{33, 36}, and the Ho-
locene oscillations may be linked to solar 
forcing (\cite{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 (\cite{37}). 
Interdecadal climate change is greatly in-
fluenced by preferred modes of variability of 
the climate system, and especially by the 
(\cite{39}) found abrupt shifts between qualitatively 
different, persistent states akin to those implica-
ted in the DO oscillation; however, pro-
gressively increasing the strength of mixing 
processes weakened and then removed this be-
havior (Fig. 4). Observations have recently in-
dicated a complex spatial structure of mixing in 
the oceans (\cite{40}); however, GCMS often have 
represented these complex processes simply as 
uniform, strong mixing, which may have con-
tributed to reduced model sensitivity to thresh-
old crossings compared to observed responses. 

**Impacts of Abrupt Climate Change on** 
Ecological and Economic Systems 

Although there is a substantial body of re-
search on the ecological and societal impacts of 
climate change, virtually all research has 
relied on scenarios with slow and gradual 
changes (\cite{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 appro-
priate scenarios of abrupt climate change for 
impacts assessments. In addition, the FCCC 
(\cite{4}) 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 envi-
ronment. Slower changes allow response 
with less disruption in both ecosystems and 
economies (\cite{e.g. (42)}). Abrupt changes are 
particularly harmful where the individual en-
tities 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 rela-
tively 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 (\cite{43}). Local extinctions and exten-
sive ecosystem disruptions occurred in re-
gions including the northeastern and central-
Appalachian United States in fewer than 50 

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**Fig. 3.** Paleoclimatic data showing abrupt climate changes, after (\cite{45}) and 
other sources. The lower panel is the history of temperature in central 
Greenland over the last 110,000 years (\cite{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 (\cite{22}) reflect production in global wetlands, including 
important tropical sources. Gray-scale of a sediment core from the 
Cariaco Basin, offshore Venezuela (\cite{73}), is plotted here so that a down-
ward 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.

**Fig. 4.** Results from a very simple, conceptual model of the Atlantic thermohaline circulation 
(THC), building on Stommel (\cite{2, 26}). The blue and red curves show steady-state THC strength as a function of the freshwater loss to the atmosphere in the sub-tropics (equal to fresh-
water gain at high latitudes). The red (blue) curve shows the case for weak (strong) mixing, which here represents either true oceanic mix-
ing or processes such as the wind-driven circu-
lation 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 arbi-
trary 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 
and ENSO and the southern and northern annular modes (\cite{38}). Strong evidence links regional abrupt cli-
mate changes to shifts in preferred modes, such as de-
pendence of droughts and floods on ENSO 
processes (\cite{13}), or de-
pendence of large Arctic changes on 
trends in the northern annular mode (\cite{16, 38}). The prominence of such climate-mode 
shifts in recent climate 
changes suggests an important role further in the 
past, and in the fu-
ture. Better representa-
tion of modes in climate models thus 
may improve simula-
tions of abrupt cli-
mate changes. 

Other model im-
provements also may 
help in simulating 
abrupt climate change. Using a simple Stom-
mel (\cite{26})-type box model of the ocean 
circulation, Marotzke 

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).

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 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 (52, 53).

Research coupling economic and climate models has progressed over the past decade, but there is virtually no linked research on 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).

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 pre-

[Image: 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).]
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 gradual climate change, policies-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 uncertainty about the nature and speed of future gradual climate change, accompanied by more uncertainty than will all possible causes of abrupt climate change, 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#pagegotop

3. Short-term climate stability is provided by the increase in longwave radiation emitted by Earth as it warms, and by cooling due to radiation at its cold end. 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 CO2 from volcanoes is nearly independent of Earth’s surface temperature, but the rate at which CO2 is removed from the atmosphere by chemical reaction with rocks increases with temperature, which increases as CO2 (66).


5. Ice-age cycles were caused by orbital induced latitudinal and seasonal redistribution of sunlight that led to changes in the amount of sunlight reflected by Earth (through changes in snow and ice, vegetation, and probably clouds and dust), in the greenhouse-gas concentration of the atmosphere (primarily CO2 and water vapor but including CH4 and N2O), and perhaps in other factors (47).


8. R. B. Alley, “Yearmean temperature for selected meteorological stations in Denmark, the Faroe Islands and Greenland” (Tech. Rep. 02-06; Danish Meteorological Institute, Copenhagen, 2002); available at www.dmi.dk/f-1/u/publikation/teknar/2002/TechRep-02-06.pdf.


25. North Atlantic records show a repeated pattern, often with ~1500-year spacing, of abrupt warming followed by gradual cooling, abrupt cooling, and a few cold centuries. Generally cold, dry, and windy conditions occurred together across much of the Earth, although with antiphase behavior in some far southern regions. The anomalously mild times following the abrupt warmings are often called Dansgaard-Oeschger (DO) events. We follow some workers in referring to the DO oscillation, without necessarily implying strict periodicity (6). At least some of the cold phases immediately followed floods or ice-sheet surges into the North Atlantic (4), including a centennial cold event about 8200 years ago with widespread impacts (45) that immediately followed a large outburst flood from a lake dammed by the melting ice sheet in Hudson Bay (67).


34. This difficulty, lack of a globalizer, is shared with the standard explanation of global ice-age cooling by reduced Northern Hemisphere summer insolation from the relatively weak 100,000-year cyclicity of orbital forcing (4).


36. Except for the event about 8200 years ago, the Holocene changes differ from the DO oscillations in many ways, with Holocene changes smaller, of less clear but probably reduced spatial extent and uniformity, and lacking the global abrupt perturbations of biogeochemical cycles shown by shifts in trace gases such as CH4, N2O, and CO2 in the ice-age events (6).


45. R. B. Alley et al., *Geol. 25, 483 (1997).


48. Ecosystems and economies can be forced across thresholds by gradual as well as by abrupt climate changes, causing major abrupt impacts, although faster forcing is probably more likely to cross impact thresholds.


52. J. Reilly, N. Hohmann, S. Kane, *Climate Change and Agriculture: Global and Regional Effects Using an


57. One prominent warm interval was the Paleocene-Eocene Thermal Maximum (68), which began with warming over perhaps 10,000 to 20,000 years or faster of about 4° to 8°C in high-latitude ocean surface temperatures and 4° to 6°C in bottom-water temperatures from conditions that were already warmer and with an equator-to-pole temperature gradient that was smaller than occurred recently. A change in location of deep-water formation may have led to massive destabilization of methane hydrate in sea-floor sediments. Impacts included extinction of 30 to 50% of benthic foraminifera and subtropical drying.

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 palaeoclimatic 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.


64. L. K. Barlow et al., Holocene 7, 489 (1997).


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