CLIMATE SHOCK: ABRUPT CHANGES OVER MILLENNIAL TIME SCALES

How will Earth's climate respond to ongoing changes in greenhouse gases and ocean circulation? Answers about the future might be found in the past.

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What is the natural variability of our climate? This simple question is, in fact, very hard to answer, from either the theoretical or observational point of view. However, it is of utmost importance if we really want to detect and predict the consequences of human activities that have altered several components of the climate system, the most noticeable change being a considerable increase in atmospheric carbon dioxide from the burning of fossil fuels.

The climate system is complex because it is made up of several components (such as the atmosphere, oceans, and ice sheets), each of which has its own response times and thermodynamic properties. Those components not only interact nonlinearly with each other, but are connected to other complex systems such as the carbon cycle, which regulates greenhouse gas concentrations in the atmosphere. The climate can be affected by various types of so-called external forcings or influences (such as changes in insolation) that have different spatial and temporal scales of propagation in the system. A further problem is that internal rearrangements and resonances make it difficult to determine a true equilibrium state. Indeed, the steady state is characterized by a significant noise level and oscillations that are not always easy to distinguish from real transient changes of the global climate.

Unstable models

The complex climate system has been studied theoretically for the case of the ocean–atmosphere couple. Based on various types of simulations ranging from simple models with a few homogeneous reservoirs to full general circulation models,[1] it is now recognized that the ocean–atmosphere system exhibits several stable regimes under equivalent external forcings. The transition from one state to another occurs very rapidly when certain climatic parameters attain threshold values. Such nonlinear behavior can be illustrated by a hysteresis loop, shown in figure 1, that represents the temperature in the North Atlantic Ocean and on adjacent continents as a function of freshwater flux into the North Atlantic (mainly from rain, rivers, and melting icebergs). The freshwater flux affects the density of surface waters, which in turn controls the large-scale convection occurring in the northernmost part of the Atlantic Ocean. At the present time, the surface waters in the northern seas become so dense that they sink to the abyss, and that overturning, called the North Atlantic Deep Water (NADW) flux, ventilates the deep layers of the global ocean. The convection process is maintained by a continuous supply of shallow water advected from tropical regions. The NADW flux belongs to a wider convection system, known as the global thermohaline circulation and often represented as a conveyor belt, that connects the world's ocean basins.

According to models, a slight increase in the freshwater flux above the modern level F produces a decrease in the NADW convection and a moderate cooling in the North Atlantic (see the upper part of figure 1). However, the system flips to another state once the flux reaches a threshold value $F + \Delta F$. That state, which has no deep convection, is characterized by surface temperatures up to 6°C lower in and around the North Atlantic. Such a drastic transition, known as a bifurcation, can occur very rapidly—over a period of decades. The cold state is also quite stable: The freshwater flux must be decreased significantly to another threshold value ($F - \Delta F'$) before the system can flip back to its original warm state.

That hysteretic mechanism is not the only cause of climatic variability, and other types of nonlinear behavior are known to exist. Another example of feedback and amplification is associated with drought over land areas at low latitudes. In wet climates, rainwater is captured by roots, absorbed by plants, and then returned to the atmosphere, where it may give rise to a significant amount of additional rainfall. By contrast, in dry climates, much of the rainfall runs off to supply the groundwater, streams, and oceans, and thus reduces any further rainfall.

Evidence for abrupt climate swings

Do we really have any hard evidence for such abrupt warm–cold and cold–warm transitions? Fortunately for human societies, such severe and prolonged climate change has never occurred during the historical period. We therefore need to make use of paleoclimatology—the study of the climate before written technical records began being kept—to access much longer time series under a wide range of external forcing conditions. During the past decade, many researchers have studied ice cores drilled from the Greenland ice sheet and deep-sea sediment cores from the North Atlantic. Both types of archive can be dated and precisely synchronized by different techniques, as described in the box on page 34. Paleotemperatures in Greenland are derived from stable isotope measurements (oxygen-18/oxygen-16 and deuterium/hydrogen ratios) on water molecules from the ice.[2] Sea-surface temperatures (SST) can be evaluated, among other techniques, by analyzing specific molecules (the so-called alkenones) that are synthesized by phytoplankton and well preserved in sediments.[3]

Over the past 100 000 years, the temperature fluctuations in Greenland and the North Atlantic are clearly parallel to each other, as seen in figures 2a and 2b. The most notable features are millennium-scale warm events, which are particularly marked in Greenland (increases of more

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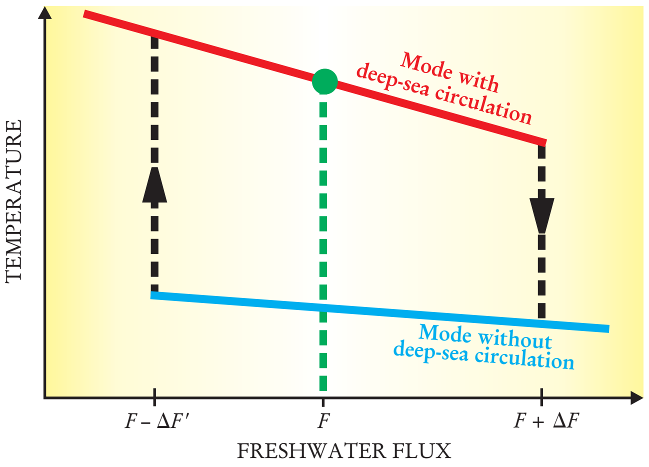

FIGURE 1. CONCEPTUALIZED CLIMATE SYSTEM representing the temperature in and around the North Atlantic Ocean as a function of freshwater input to the northern North Atlantic. The upper branch (red) features strong deep circulation. Along the lower branch (blue), the circulation is collapsed. The modern climate, with its freshwater flux F, is on the upper branch, as shown in green. When the fresh water reaches a threshold ($F + \Delta F$), the system flips rapidly to the lower, cold regime. Going back to the warm mode would require a greatly reduced freshwater input ($F - \Delta F'$). This diagram is highly schematic; the exact position of the modern climate with respect to bifurcation points is largely unknown. Moreover, the shape (particularly the width $\Delta F + \Delta F'$) of the hysteresis loop depends on parameters that are external to the ocean–atmosphere system. (For more details, see refs. 1, 5, 11, and 14.)

than 10°C) but are relatively subdued in the North Atlantic. And although not so clearly seen in the Greenland ice cores, several drastic cooling events stand out in the oceanic record. They are easily picked out because the corresponding marine sediments in core samples contain distinctive types of debris carried along by icebergs.[3,4] Figure 2c shows such a record[3] measured in the same North Atlantic sediments as those used to reconstruct the SST time series of figure 2b. As the different records show, each period of increased iceberg rafting is accompanied by drastic cooling of up to about 5°C.

Although the variability illustrated in figure 2 is based on two particular sites, the climate swings were widespread in the North Atlantic and over Greenland. The warm intervals are called Dansgaard–Oeschger events in honor of the two pioneering glaciologists, Willie Dansgaard at the University of Copenhagen and Hans Oeschger at the University of Bern, who, in the early 1980s, identified and described the events in Greenland ice cores. The distinct layers containing ice-rafted debris are found everywhere between 40 and 60°N in the North Atlantic. Their importance was first recognized by Hartmut Heinrich in the late 1980s. The so-called Heinrich events originated mainly from the Laurentide ice sheet covering Canada, as illustrated in figure 3, and led to the transport of fine-grained sediments eroded

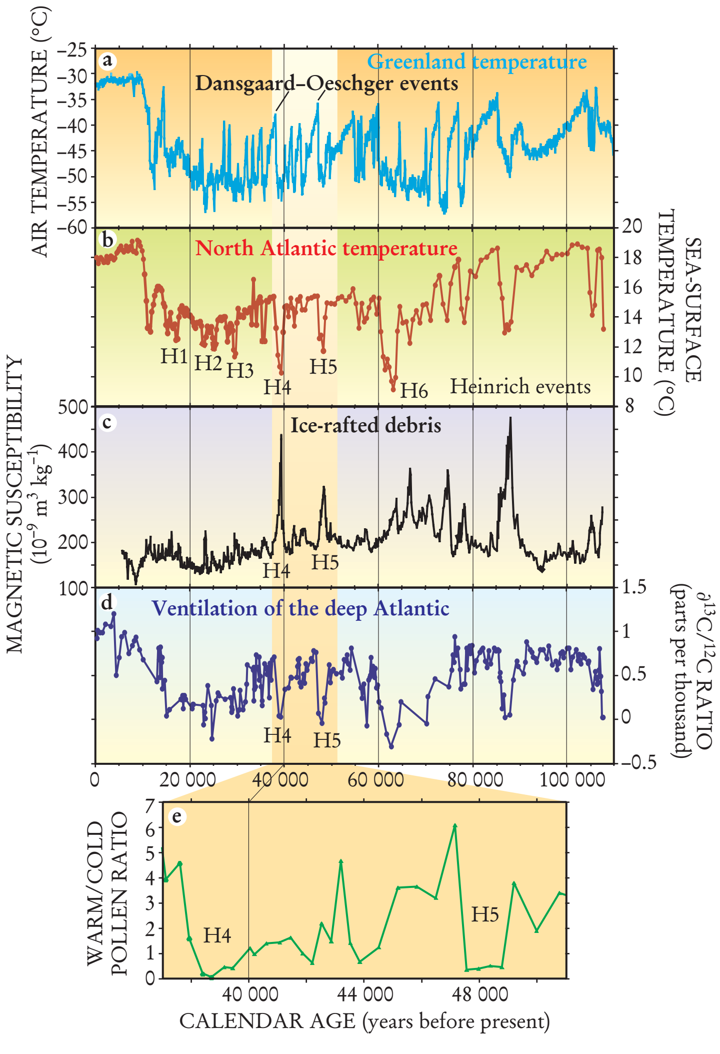

FIGURE 2. CLIMATIC AND OCEANOGRAPHIC variations in and around the North Atlantic Ocean during the past 110 000 years, as revealed in Greenland ice cores and North Atlantic sediment cores obtained off the Iberian Margin. Time progresses from right to left. **(a)** The Greenland air temperature based on isotope thermometry shows abrupt warm periods called Dansgaard–Oeschger events. The records were obtained from ice cores by Willie Dansgaard, Sigfus Johnsen, and their collaborators in Copenhagen, Denmark. **(b)** The sea-surface temperature in the North Atlantic shows episodes of drastic cooling called Heinrich events. This record compiles our results on biomolecular thermometry with long-chain (37-carbon) organic molecules called alkenones measured on two sediment cores at CEREGE (Aix-en-Provence, France). **(c)** The presence of ice-rafted debris, which was revealed in the sediment magnetic property measurements by Nicolas Thouveny and colleagues at CEREGE, is correlated with the drastic cooling in Heinrich events. **(d)** The ventilation of the deep Atlantic has been reconstructed by Nicholas Shackleton and his colleagues in Cambridge, UK, from variations in the carbon-isotope ratio contained in bottom-dwelling benthic foraminifera found in the sediment cores. **(e)** A qualitative measure of the continental climate is the ratio of pollen from temperate plants to that from cold-climate plants, as measured in marine sediments by Maria-Fernanda Sanchez-Goni and her collaborators in Bordeaux, France. The methods used to generate these records are described in the box on page 34. (Ice-core data from ref. 2; sediment-core data from ref. 3.)

The Paleoclimatology Toolbox (Opening a Can of Worms!)

For periods before the past few centuries, there is unfortunately no direct way to measure climatic and oceanographic parameters such as temperature, precipitation, ice cover, or strength of ocean currents. Paleoclimatologists and paleoceanographers have thus developed a battery of so-called paleoproxies that can be empirically calibrated to the climatic parameters of interest. Most of these paleoproxies are based on the analysis of chemical, physical, and biological properties in geological archives such as sediments from oceans and lakes, ice from mountain glaciers and large continental ice sheets, groundwater from deep aquifers, and stalagmites and other cave deposits.

Dating these records is a prerequisite step that depends on the age and nature of the archive itself. The most precise dating can be achieved when seasonal layers are preserved, as in large trees, massive corals, and recent glaciers. Layers can also be found in relatively rare ocean and lake environments; such layers are called varved sediments. However, dating with annual resolution is limited to the past few millennia. Other dating methods are based on the natural decay of radioactive isotopes. On the 10^4–10^5-year time scale of interest for this article, precise ages are obtained using carbon-14 and thorium-230/uranium-234 measurements. Although both methods were invented in the 1950s, their precision and accuracy have been boosted during the past decade by new mass spectrometric techniques.

Past temperatures in Greenland are derived from stable isotope measurements on waters melted from the polar ice. Atmospheric temperatures will affect the relative abundances of various isotopes in the ice, liquid, and vapor phases—an effect termed fractionation. The snow falling on Greenland shows a rather large dynamic range of oxygen-18/oxygen-16 and deuterium/hydrogen ratios, from which a record of past temperatures can be extracted. The paleotemperatures obtained this way have been recently corrected and corroborated using other physical and geochemical techniques.[17]

In the marine realm, two kinds of methods are commonly applied for the basinwide mapping of surface paleotemperatures:[18] those based on chemistry, which use a variety of markers (trace metals, stable isotopes, and organic molecules), and those based on abundances of microfossil species, which rely on a variety of statistical techniques.

Long-chain alkenones are lipids that are present in several types of algae. The number of double bonds identified in these molecules is useful for reconstructing the ancient sea-surface temperature (SST). Laboratory algae cultures show a clear correlation between the growth temperature and the relative abundance of the di- and tri-unsaturated alkenones (those with two and three double bonds). Similarly, using modern (core-top) algae-containing sediments, several workers have found a clear covariation between the unsaturation ratio and the SST. That relationship is applied to paleorecords, but it is largely empirical. It appears that the microscopic algae can maintain the viscosity of their internal fluids by adjusting the relative abundance of their lipids. A useful parallel is provided by the large viscosity difference between common unsaturated triglyceride oils (such as soya, cotton, and sunflower oil) and the corresponding saturated fats (margarine). The alkenone technique works as a proxy because the viscosity is also related to the ambient temperature.

Oxygen isotope data based on the shells of surface-dwelling planktonic foraminifera have been used in support of temperature reconstructions, but rarely as a standalone temperature index because of the large influences of other environmental parameters on the measured ^{18}O/^{16}O ratio (see PHYSICS TODAY, December 2001, page 16). Other chemical methods include those based on trace element ratios such as strontium/calcium, uranium/calcium, and magnesium/calcium in the carbonate skeletons of corals and microfossils (shells of planktonic and bottom-dwelling benthic foraminifera). The general assumption is that trace metals are incorporated into the carbonate lattice at concentrations that depend on growth temperature. However, observations rarely agree with thermodynamic considerations, because living organisms nearly always introduce additional complexity. (Specialists use the generic term vital effects, which hides their lack of knowledge about still poorly characterized mechanisms.)

Water-column properties can be estimated by considering the abundance of various faunal or floral species. The process relies on statistical prediction methods that are entirely empirical. Using modern (core-top) samples, such abundances can be correlated with SST or some other property of the ocean. The primary assumption is that, at any given site, the changes with time are controlled by the same mechanisms that influence the modern spatial patterns of faunal abundance. As one example of such statistical techniques, records of the relative abundance of so-called dysoxic benthic foraminifera, which are adapted to oxygen-poor conditions in marine bottom waters, can be used to extract information about oxygen depletion in the oceans. Similar statistical techniques are used with lake and marine sediments to study trapped pollen from warm- and cool-climate plants.

The strength of the deep-sea ventilation can be studied with several geochemical proxies based on trace elements (such as cadmium), radioactive isotopes (^{14}C or protactinium-231, for example) and stable isotopes (such as ^{13}C). Again, the relationships between the paleoproxy and the deep circulation are often empirical and depend on biological processes that fractionate chemical and isotopic species during the slow movements of water masses. For example, photosynthesis and biological activity preferentially use up the more reactive ^{12}C in surface waters, whereas the dissolution of sinking fecal pellets progressively enriches deep waters in ^{12}C. Thus, water currently or recently at the surface is depleted in ^{12}C and enriched in ^{13}C compared to water that has been in the deep ocean for a long time. Furthermore, the deep Pacific waters, due to the longer time since their last contact with the surface, are depleted in ^{13}C by about one part per thousand compared to deep Atlantic waters.

Other biological processes that fractionate isotopes can be exploited in paleoceanography. For example, marine bacteria typical of oxygen-depleted zones preferentially use nitrogen-14 when converting marine nitrates (dissolved NO_3^-) into gaseous nitrogen (N_2O and N_2), leaving the remaining NO_3^- enriched in ^{15}N. Measurements of the ^{15}N/^{14}N ratio in organic matter preserved in ocean sediments can thus be used to track changes in the denitrification processes that are usually associated with oxygen depletion in the ocean.

Another kind of paleoproxy is constructed by considering the sedimentary abundance of minerals and organic compounds linked to specific oceanographic or climatic processes. For example, the flux of icebergs can be evaluated qualitatively by counting under a binocular microscope the individual grains of continental rocks transported by icebergs (so-called ice-rafted debris) or by measuring directly their total magnetic susceptibility.

To a certain degree, all paleoproxies suffer from uncertainties due to perturbations by other environmental variables and to problems related to signal preservation. Such complications are inherent to geological archives because, by their nature, all paleoproxies are linked in some way to a variety of complex natural processes. Admittedly, the uncertainties represent the main weakness of paleoclimatology and paleoceanography in contrast to modern climatology and oceanography. However, researchers can justify the use of multiproxy reconstructions because, in principle, most of the sources of systematic error (or bias) should cancel out because they are specific to certain biological groups or analyzed chemical species.

from the underlying rocks. The distribution of these discrete melting events can be mapped precisely by studying the mineralogical, geochemical, and physical properties of the ice-rafted component of sediments.[4]

The record of deep-ocean ventilation is also correlated with the temperature time series, as expected from ocean–atmosphere modeling. The ventilation record can be extracted from the same marine sediments used for studying alkenones and ice-rafted debris. It is based on the carbon isotopes contained in the microscopic shells of unicellular organisms that live on the ocean bed (see the box). These so-called benthic foraminifera pick up their $^{13}C/^{12}C$ ratio from the inorganic carbon dissolved in bottom waters, which itself depends on the oceanic ventilation. High $^{13}C/^{12}C$ ratios in North Atlantic benthic foraminiferal shells imply vigorous overturning, whereas low $^{13}C/^{12}C$ ratios indicate sluggish deep-sea circulation. The record given in figure 2d shows that the North Atlantic convection over the past 100 000 years varies essentially among three states: The highest $^{13}C/^{12}C$ values are observed for the recent past; further back in time, the ocean oscillated between two states, one characterized by $^{13}C/^{12}C$ values that were relatively high but lower than modern, and the other by still lower values. As the sedimentary records in figure 2 show, each short period of intense iceberg melting is associated with a distinct decrease in North Atlantic ventilation.

Drastic cooling events also affected the nearby European continent, as revealed in the plant pollen found in the same deep-sea sediments that were analyzed for carbon isotopes and alkenones. The painstaking work of counting pollen was performed for a short time interval between 30 000 and 50 000 years before the present. Figure 2e shows the time evolution of the abundance ratio between the pollen of plants (mainly deciduous trees such as oak) typical of temperate and humid climates and pollen of plants (such as shrubs) typical of cold steppes. The pollen ratio is a useful qualitative measure of climate over the continents, with high values observed during mild periods and low values during the colder events of intense iceberg melting.

Simulating millennium-scale transients

Taken together, those observations seem to support the theory that rapid climatic changes are due to abrupt transitions of the state of the ocean–atmosphere system, as represented by the simplified hysteresis loop of figure 1. The high degree of correlation between temperature records and ocean ventilation records is probably the best "fingerprint," indicating that both ocean and atmosphere were intimately involved in the abrupt fluctuations. The excess freshwater flux into the North Atlantic over the past 100 000 years is clearly linked to massive influxes of meltwater from icebergs.

Several modelers have attempted to simulate the millennium-scale climatic variability of the last glacial period of 10 000–100 000 years ago, particularly the complex interplay between Dansgaard–Oeschger warm phases and Heinrich cold events. At present, models coupling the atmosphere, ocean, and ice sheets are still unable to correctly simulate that variability on all scales in both time and space. To date, all the attempts have been made with simplified models using some kind of imposed forcing factor.[1]

One of the most impressive results so far has been obtained by Andrey Ganopolski and Stefan Rahmstorf at the Potsdam Institute for Climate Impact Research in Germany. They perturbed a simplified ocean–atmosphere model with a variable freshwater flux into the North Atlantic.[5] As shown in figure 4, this system exhibits a typical hysteresis behavior that is excited by a freshwater flux cycle of relatively limited amplitude. The Atlantic Ocean responds in a highly nonlinear way with abrupt and large amplitude changes in its general overturning rate. These fluctuations generate temperature cycles of very large amplitude both at high latitudes in Greenland and at mid latitudes in the North Atlantic.

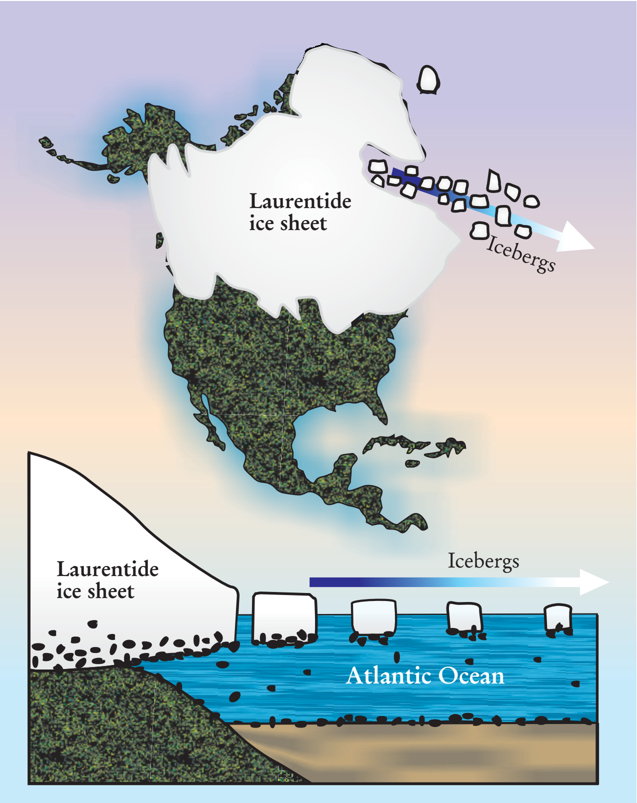

FIGURE 3. DURING A HEINRICH EVENT, icebergs surge into the North Atlantic Ocean. The lower panel illustrates the entrainment of debris (black) by icebergs and the subsequent sedimentation of the debris in the deep North Atlantic.

A highly diagnostic feature is the asymmetric shape of the warm events, especially for Greenland: The temperature warms abruptly to reach a maximum and then slowly decreases for a few centuries before reaching a threshold, after which it drops back to the cold values that prevailed before the warm event. Although the Dansgaard–Oeschger events vary in duration, as seen in figure 2a, they have the same asymmetric shape as reproduced by the numerical model. The abrupt warming results from a northward advection of warm Atlantic waters into northern seas; the plateau phase corresponds to the "warm mode" of Atlantic Ocean circulation that gradually weakens, and the rapid cooling marks the end of deep-water formation in the northern seas.

Another key feature is the spatial distribution of the modeled warming event shown in figure 4e. This map clearly shows that maximal warming is centered on the northern Atlantic; farther away, its impact fades, becoming much smaller in the Pacific Ocean region and almost negligible in the Southern Hemisphere.

Such characteristics are fully compatible with existing paleoclimatic data, which show that temperature variations were much smaller in the intertropical zone.[6] However, these relatively small changes are greatly amplified in the water cycle: Because the saturated water vapor pressure

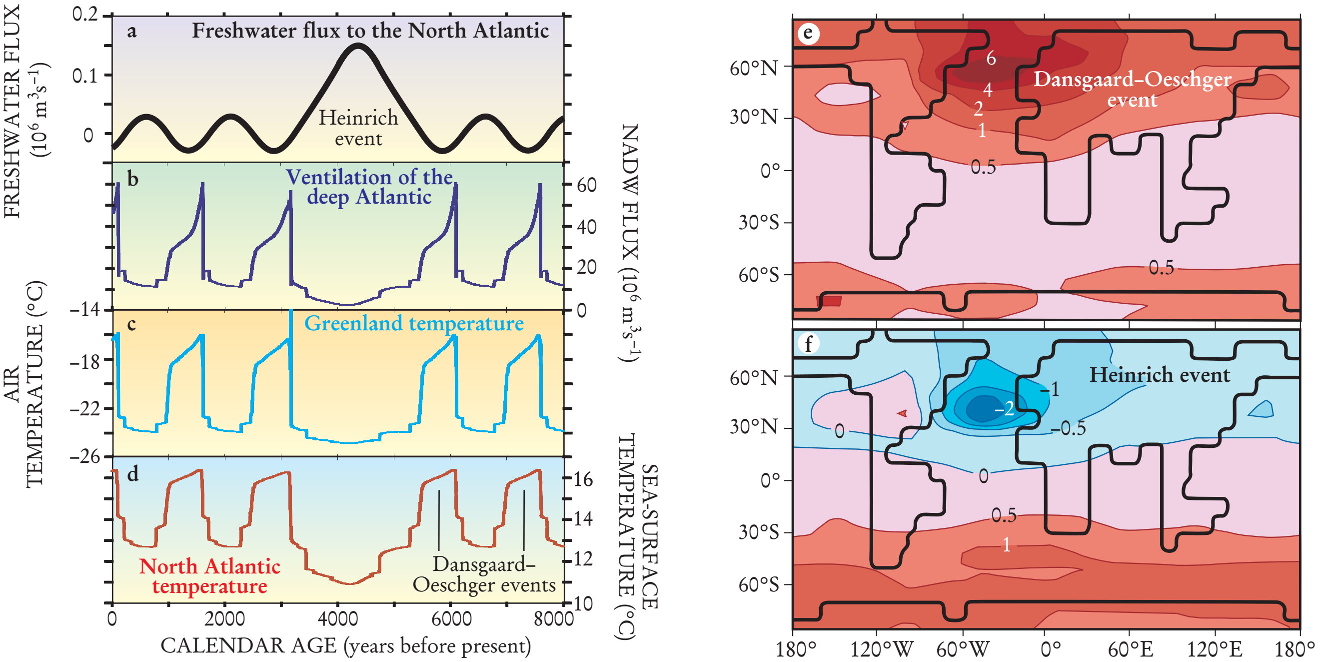

Figure 4. Major features of past climate variations have been recreated using a climate model of intermediate complexity.[5] **(a)** Freshwater flux is the key input to the model. Small perturbations with a 1500-year cycle are sufficient to generate Dansgaard–Oeschger warming events; a large freshwater input represents a Heinrich event. **(b)** Resulting variations of the Atlantic ventilation, expressed as the North Atlantic Deep Water (NADW) flux. **(c)** Variations in the air temperature over Greenland. **(d)** Variations of the sea-surface temperature in the North Atlantic mid latitudes. **(e)** Maximum air temperature anomaly attained during the warm transient of a Dansgaard–Oeschger cycle. The black outlines show the crude continent locations. **(f)** Maximum air temperature anomaly reached during an iceberg surge associated with a Heinrich event. The greatest cooling during Heinrich events is found farther south than the greatest warming during a Dansgaard–Oeschger event.

rises exponentially with temperature, rather small temperature changes in warm zones translate into relatively large changes of water availability. Indeed, researchers working on tropical paleoclimates see evidence that large changes in moisture availability and tropical rainfall occur during Dansgaard–Oeschger warming events.[7]

To mimic a Heinrich event, the same model was perturbed using a major freshwater input into the North Atlantic.[5] Such a large flux literally kills off the deep-sea circulation, which causes a widespread cold event (figure 4f) that is relatively more pronounced in the mid latitudes of the North Atlantic, lower than the latitudes showing maximal warming in Dansgaard–Oeschger events. Another characteristic feature of the modeled temperature distribution is that the intense cooling centered in the North Atlantic is accompanied by a widespread warming in the Southern Hemisphere. This seesaw effect results from the reduced interhemispheric heat transport and the enhanced formation of Southern Ocean deep water when NADW formation is reduced. Evidence for such a seesaw effect is provided by comparisons between ice-core records from Greenland and Antarctica. In particular, the most recent temperature oscillations in Greenland between 16 000 and 11 000 years ago are in antiphase with those observed in central Antarctica.

Over the past few years, evidence has been emerging that the Dansgaard–Oeschger and Heinrich events had a strong and widespread impact on the marine carbon cycle. A global estimation of that effect still requires more work, but several studies have shown that the amount of organic matter in sediments from several oceanic areas varies in phase with the Dansgaard–Oeschger and Heinrich events. Convincing records have been obtained not only in the North Atlantic but also in the North Indian and West Pacific Oceans;[8] figure 5 shows a few examples. The changes have been attributed to large fluctuations of the biological productivity in surface layers of the ocean. Their abruptness could be linked to the injection of nutrients into the surface layer by wind-induced mixing and upwelling. An additional cause could be the direct input of biolimiting elements in dust transported by low-latitude winds.

At best, though, the concentrations and mass fluxes of marine organic matter in sediments show only a qualitative correlation with the biological productivity occurring in the surface layers. The preservation of organic compounds depends on ambient conditions in the water column, in particular its oxygen content. Oceanic zones of high biological productivity are characterized by pronounced oxygen depletion at intermediate water depths. Ocean convection transporting oxygen-rich water masses may thus have played an additional role in shaping the organic records. As described in the box, several techniques can be used to evaluate the severity of oxygen depletion at intermediate depth; figure 5 shows two examples.

The timing and duration of Dansgaard–Oeschger and Heinrich events have been the subject of many hot debates. In 1993, Gerard Bond from Columbia University identified some regularity by comparing Greenland and North Atlantic time series: The millennium-scale events are apparently distributed according to long-term cycles, with warm periods becoming progressively shorter and cooler. Each long-term cycle culminates in a prolonged cold period during which a Heinrich event takes place. Other workers have applied a variety of frequency-analysis tech-

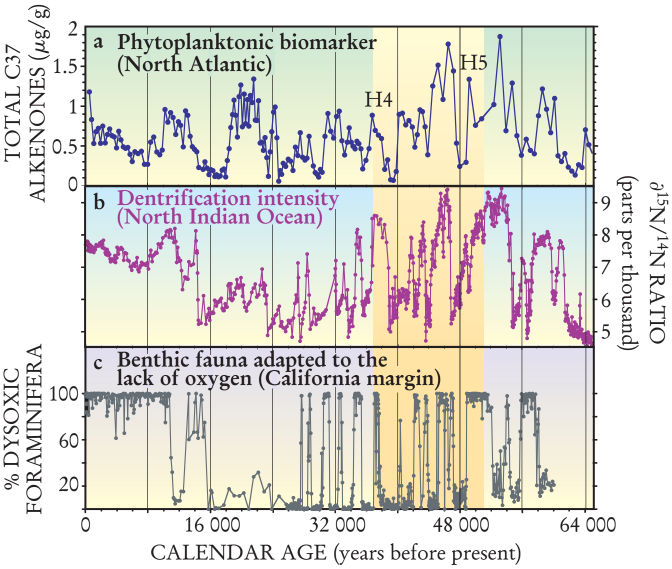

Figure 5. Dansgaard–Oeschger and Heinrich events are reflected in records of the marine carbon cycle during the last 65 000 years. **(a)** Concentration of 37-carbon alkenones, a phytoplanktonic biomarker in North Atlantic Ocean sediments. We obtained this record at CEREGE on a core sampled off the Iberian Margin. **(b)** The nitrogen-15/nitrogen-14 ratio in organic matter preserved in North Indian Ocean sediments was measured by Mark Altabet from the University of Massachusetts Dartmouth and his colleagues, and is correlated to the oxygen depletion caused by biological activity in the ocean. **(c)** Oxygen depletion is also reflected in the relative abundance of benthic foraminifera that have adapted to the lack of dissolved oxygen in marine bottom waters. The record shown was obtained on sediments from the California Margin by Jim Kennett and his collaborators at the University of California, Santa Barbara. The methods used to generate these records are described in the box on page 34. (Data from ref. 8.)

niques. That task has proved to be more complex than expected because of the highly asymmetrical shape of the cycles and potential mathematical artifacts linked to sampling. Indeed, the predominance of an underlying 1500-year cycle has often been proposed but remains controversial; a simple inspection of figures 2a and 2b shows that the records are far from being a simple sine wave. Michael Schulz from the University of Bremen recently demonstrated that the prominent 1500-year spectral peak is caused by just three events that represent only 5% of the total duration of the glacial period (between 30 000 and 35 000 years before the present, visible in figure 2a).[9] Other recent studies by Richard Alley at Pennsylvania State University and by the Potsdam group suggest that the Greenland record, by amplifying small fluctuations of freshwater flux into the North Atlantic, exhibits the regular behavior typical of a stochastic resonance system.[10]

Could it happen again?

Although no model has yet reproduced the detailed climatic variability that occurs during a glacial period, the general match between observational data and modeling strongly suggests that the envisaged mechanisms are plausible. Another lesson from the modeling approach is that the ocean–atmosphere system is particularly sensitive and unstable during glacial periods.[5,11] Compared to the last glacial period, the modern climate is characterized by differences in conditions such as ice-sheet distribution, insolation variations, and greenhouse gas concentrations in the atmosphere. Under the present boundary conditions, the hysteresis loop appears to be significantly wider than during glaciations. In other words, the modern climate is probably less prone to frequent jumps between two extreme states. Indeed, the best evidence that the modern climate is relatively stable is provided by the temperature records in figure 2. During the Holocene period, which covers the past 10 000 years, both the Greenland and North Atlantic temperatures define smooth and limited decreasing trends. Paleotemperatures reconstructed for low-latitude areas confirm the relative stability of the Holocene, although records obtained for land areas indicate a somewhat larger variability in the water cycle and associated components such as lake levels and vegetation cover.

The only important event during the Holocene, occurring about 8200 years ago, was much smaller and shorter than the glacial swings.[12] Sedimentological and glaciological studies suggest that this early Holocene cooling was due to freshwater input into the North Atlantic. Lakes located on the melting front of the Laurentide ice sheet supplied a sudden input to the ocean when their drainage was diverted toward the Hudson Strait at the very end of the last deglaciation.

During the glacial period, the 4-km-thick Laurentide ice sheet greatly depressed the underlying land. Due to the long relaxation time scale (a few millennia) for Earth's viscoelastic rebound, the ice melted back into its own hole. Because the ice was centered on Hudson Bay, blocking off the Bay as well as its outlet, extensive lakes (including the largest lake on Earth at that time) formed around the ice and could not drain away. Eventually, as the ice shrank, the meltwater managed to escape. It is now understood that such glacier bursts are invariably catastrophic. The heat from turbulent drainage flow increases the size of the opening, thus enlarging an ice-walled channel. Through such a process, it is likely that the largest lake on Earth emptied into the North Atlantic during the space of a single summer to a few years. This emptying was immediately followed by a widespread cooling, probably because the fresh water favored sea-ice formation in the North Atlantic. That dramatic event likely had a transient impact on Atlantic overturning, at least its component in the Labrador Sea.

The early Holocene event is significant not only due to its magnitude (even though some earlier changes were larger), but also because it shows that a warm climate can be perturbed suddenly in a major way. Moreover, that event provides an outstanding test bed for numerical models because some of the conditions, such as ice-sheet dimensions, are more closely comparable to modern conditions than earlier events of greater magnitude.

Starting in 1985, Wallace Broecker from Columbia University warned that the global thermohaline circulation might be the Achilles' heel of our climate system.[13] According to him, ocean stability may not hold under future global warming, which will certainly alter the water cycle and hence the Atlantic freshwater budget. Improved models allowed Broecker's warning to be tested in 1997 by Thomas Stocker and Andreas Schmittner in Bern, Switzerland.[14] Their transient simulations showed that, when the fossil-fuel burning rate exceeds a particular threshold, the modern climate could flip to another mode characterized by cooling over the North Atlantic. That regional cooling would be associated with a strong decrease in the Atlantic overturning, reminiscent of the scenario that prevailed during Heinrich events.

Over the past few years, several other climate models of increasing complexity have been used to study the amplitude, duration, and onset conditions of what are now referred to as "climatic surprises."[15] Modeling of the ocean-atmosphere couple is still in its infancy, and the exact geometry of the hysteresis loop (figure 1) is not well known, even for the modern system. In addition, we still have no constraint on the position of the modern climate on the upper branch of the loop. For these reasons, an intense debate continues in the modeling community about the reality of such instabilities under warm conditions.

All the studies so far carried out fail to answer the crucial question: How close are we to the next bifurcation? This is an urgent problem because modern hydrographic records indicate a rapid freshening of North Atlantic waters, which suggests that the deep Atlantic ventilation has steadily changed over the past 40 years.[16] A possible answer to the question may come after major improvements in climate models, which could be achieved by increasing the spatial and temporal resolution of numerical calculations and by taking better account of the physical processes that link the different components of the climate system. The performance of such a new generation of climate models should first be tested on recent oceanographic changes, but also on longer paleoclimatic time series. In addition to technical advances, any predictions about the climate of the next century will also depend on scenarios of greenhouse gas emission over the coming years.

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