Abrupt climate change

Many aspects of the climate system are not yet sufficiently understood and are the subject of current research and scientific discussion. An example: the mechanisms of abrupt climate change which have repeatedly occurred throughout earth's history and whose causes are a matter of controversy.

Stefan Rahmstorf

Ice cores can be used to reconstruct the history of the climate over the past one hundred thousand years. This is a picture of Dr. Sigfús Johnsen in the laboratory, analysing a 50,000-year-old-sample of ice extracted from a depth of 3,400 m.

Ice-drilling projects in Greenland have provided scientists with information of hitherto unknown quality on the history of our climate over the past one hundred thousand years. Most notable are the European GRIP and American GISP2 projects on the summit of the Greenland ice sheet, which were concluded in 1992 and 1993 respectively. They are rightly considered one of the outstanding scientific achievements of the 20th century and have fundamentally altered our understanding of the dynamics of climate.

Greenland ice is made up of many thousands of layers of snow which are accumulated year after year and slowly compress the older snow underneath into ice. With the aid of sophisticated analytical methods, the ice cores reveal the history of our climate almost like a book, each layer of snow representing a separate page.

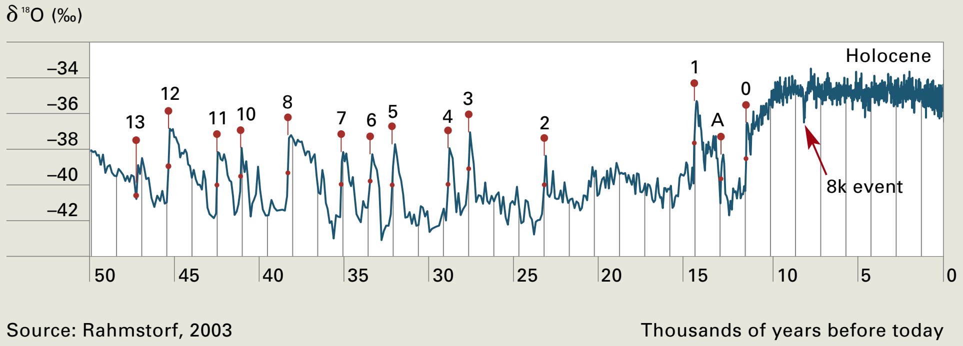
Many climate researchers were shocked by the history revealed by this icy book (Fig. 1). Until then, they had assumed that climate changes in gradual cycles – such as the Milankovich cycles with periods of 23,000, 41,000, and 100,000 years – which are caused by irregularities in the Earth's orbit around the sun and which were already known from cores drilled in deep-sea sediments. The new data from Greenland, however, provided a resolution in time that had never been achieved before: individual years could be identified and counted, more or less like the growth rings in trees. For the first time, they clearly and unambiguously revealed abrupt, dramatic changes in climate. The temperature in Greenland had repeatedly warmed by 8–10°C within just a few years, reverting to normal ice age levels only after several centuries. These climate warmings are known as "Dansgaard-Oeschger events" (DO events) after the men who discovered them, Willi Dansgaard from Copenhagen and Hans Oeschger from Berne. More than twenty such events have been identified during the last ice age, which lasted for a hundred thousand years. One of the key challenges for climate research ever since has been to unravel the mechanisms for these abrupt climate swings.

First of all, the researchers had to establish beyond all doubt that the spikes in the climate records represented real climate events and were not just spurious data caused, for example, by disruptions in the ice flow. The agreement between the cores obtained by the two teams at locations 30 km apart supported the idea that these were genuine climate events. Final proof came from the deep ocean, when US researchers were able to drill sediment cores from the bottom of the Atlantic with a resolution rivalling that of the ice cores. Spike for spike, the sediment layers from the subtropical ocean, thousands of kilometres away from Greenland and analysed by totally different methods, revealed exactly the same climate events as the Greenland ice. The dramatic Dansgaard-Oeschger events were indeed genuine and also large-scale climate changes, not limited only to Greenland. Since then, these events have been further confirmed by data from more than 170 locations around the planet, including New Zealand and the Antarctic, but the cause remained a mystery at first.

One thing was very clear from the deep-sea data: each climate change in Greenland must have been associated with distinct changes in ocean currents. Michael Sarnthein, a marine geologist from Kiel, identified three different circulation modes from those data: in one, the warm North Atlantic Current (the continuation of the Gulf Stream) continued up to the Scandinavian coast, more or less as is the case today. In the second, however, it only reached to somewhere south of Iceland. In the third, it had evidently ceased altogether (cf. Fig. 2).

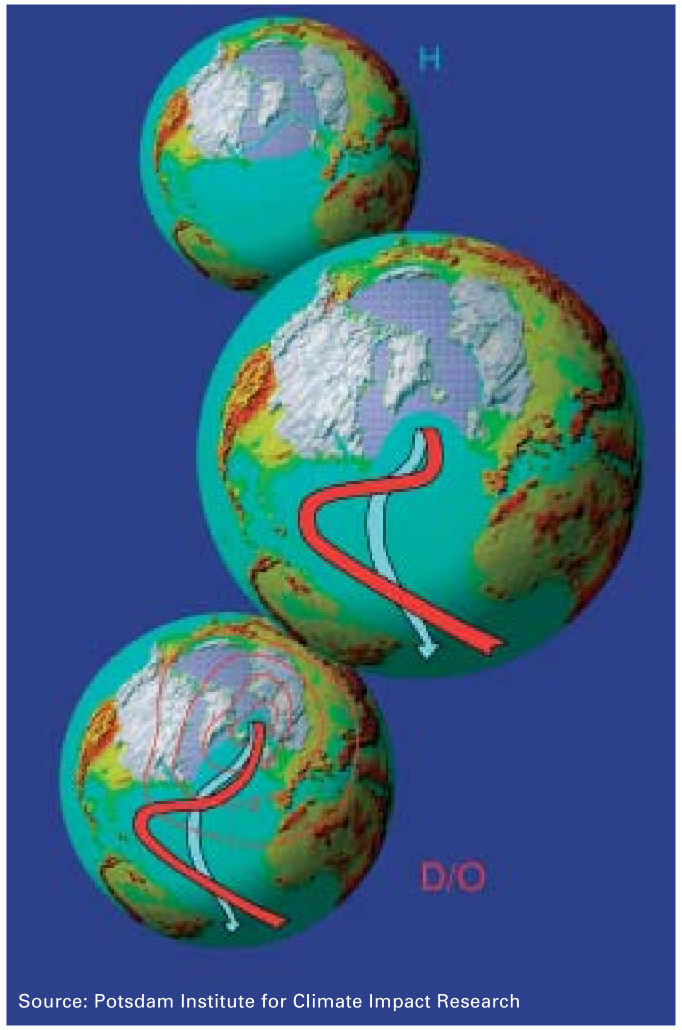
In order to understand such climate changes, research teams throughout the world are performing computer simulations of the climate system. They strive to calculate the most important aspects of climate – ocean currents and winds, air and water temperatures, cloud and ice cover, etc. – for the entire earth with the aid of basic equations of thermodynamics and hydrodynamics, as well as from empirical relations. This will never be entirely successful, but at least it is easier for climatologists to compute the climate than for meteorologists to predict the weather: while weather is dominated by chaos or at least by stochastic processes and therefore can only be predicted to a very limited extent, this fortunately does not apply to the average properties of climate.

Fig. 1 The climate history of the last great ice age – reconstructed from Greenland ice cores



Source: Rahmstorf, 2003

The figure shows a reconstruction of the temperature of the last 50,000 years based on measurements of oxygen isotope 18 in the ice. The stable interglacial period of the last 10,000 years is the Holocene; the unstable cold period preceding it is the second half of the last great ice age. Dansgaard-Oeschger events (refer to the text for an explanation) are marked in red and numbered. The vertical lines are spaced at intervals of 1,470 years; the majority of DO events are located near such lines.



Source: Potsdam Institute for Climate Impact Research

Fig. 2: Schematic illustration of three possible circulation modes in the Atlantic during the last ice age. The middle mode is the stable, cold mode prevailing in the ice age, with warm Atlantic water only flowing as far as the mid-latitudes. The situation during a warm Dansgaard-Oeschger event (D/O) with warm Atlantic water flowing right up to the Nordic Seas is shown below. The red contour lines represent the temperature rise in degrees centigrade during such an event, as calculated in our model. The globe at the top shows the situation following a total cessation of circulation in the Atlantic, as occurred after Heinrich (H) events.

(Mathematically speaking, weather forecasting is an initial-value problem; with marginally different initial conditions, the weather will develop along totally different lines after a few days. Simulating climate, on the other hand, is a boundary-condition problem, as the earth's energy balance determines the mean climate conditions.) Despite their limitations and shortcomings, computer models of the climate are already very useful tools for simulating certain situations – such as how continental ice sheets or changes in atmospheric carbon dioxide concentration affect the large-scale temperature distribution and other climate parameters. Experiments can be carried out with the computer climate that would be impossible with the real planet, for instance in order to find out how stable or unstable the climate is in a given period.

Six years ago, our team was able to present the first successful simulation of the climate prevailing at the peak of the last great ice age (around 20,000 years ago), including the ocean circulation. Other international teams followed shortly afterwards, using different models. Comparing the result of such a simulation with all the available climate data is an important test of the model's quality.

It was found at the time that changes in Atlantic currents in our model played an amplifying role in cooling the northern hemisphere. Since then, we have systematically studied the behaviour of the ocean currents under ice age conditions in numerous further experiments. On this basis we have developed a theory which might explain the mechanism underlying the abrupt changes in climate.

The three circulation modes already described by Sarnthein for the Atlantic currents (Fig. 2) were also found in our computer model. Only one proved stable under ice age conditions, namely the middle mode in which the warm current ceased south of Iceland. The other two – i.e. the one corresponding to today's Atlantic currents and the one without any warm current – could be initiated by introducing specific perturbations in the model, but the Atlantic automatically reverted to its only stable mode after a few centuries. In a warm climate, such as that prevailing today, the situation is exactly the opposite: according to our model, the two modes which are unstable under ice age conditions are now stable. The stable ice age mode, on the other hand, is not found.

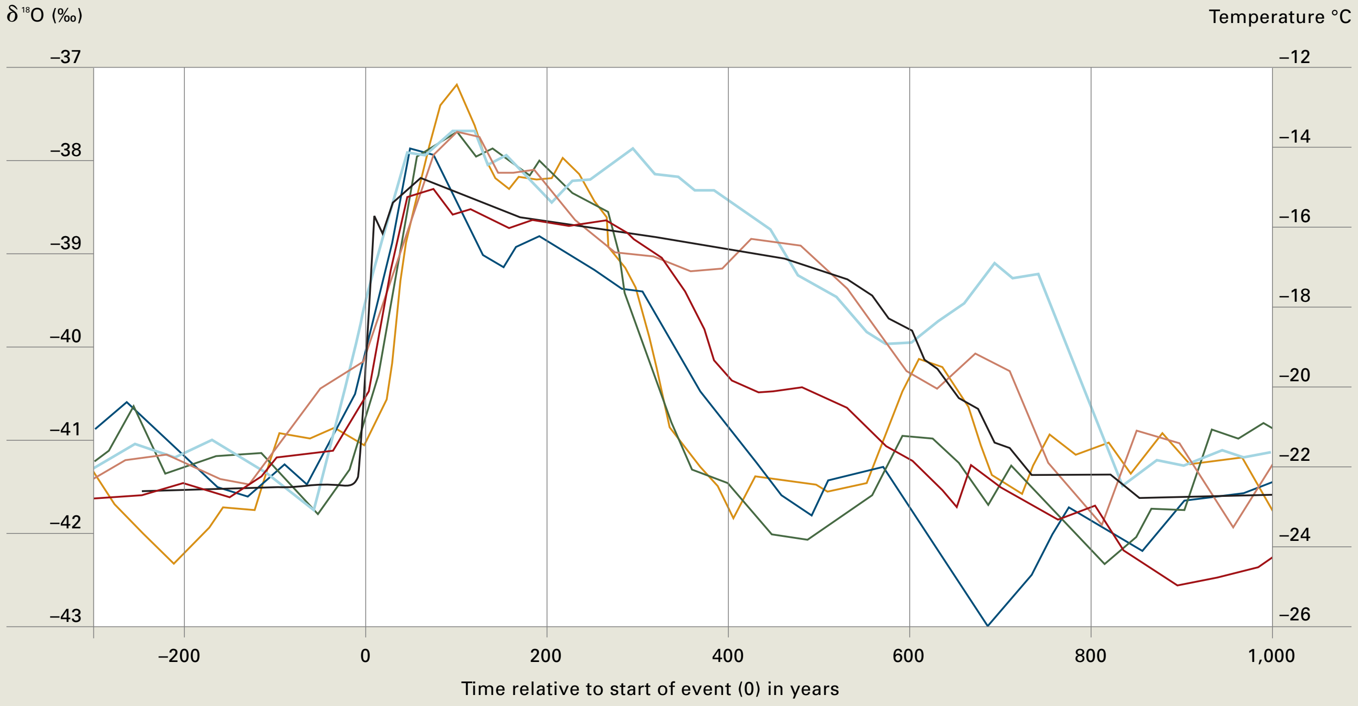
What kind of perturbation is needed to trigger one of the unstable circulation modes? In this context, it is important to know that the ocean current depends strongly on the inflow of freshwater into the North Atlantic, i.e. the total precipitation plus river runoff and meltwater minus evaporation. The inflow of freshwater determines the salinity of the seawater – and the salinity, in turn, determines the density of the water: the sinking of high-density water drives the ocean currents. To change the current, we need only change the inflow of freshwater. Since the current also transports salt, this produces a reinforcing feedback effect leading to the unique, non-linear behaviour of the Atlantic Ocean.

Model calculations indicate that a very precarious balance prevailed in the Atlantic Ocean during the ice age. Minor disruptions in the inflow of freshwater (the Achilles heel is located in the Nordic Seas, where the system is particularly susceptible to perturbations) caused the Atlantic to shift temporarily from its stable, cold circulation mode to a different mode more akin to today's climate.

Our scenario for the abrupt DO events is therefore as follows: a small disturbance in the freshwater balance of the Nordic Seas suddenly caused warm Atlantic water to flow past Iceland into the Nordic Seas, within a period of a few years. This warm water caused the sea ice to melt and the temperature of the entire region to rise. The current then gradually weakened over the centuries, until it dropped below a critical point where the warm current ceased again. Fig. 3 shows the temperature evolution for this scenario, which can explain the three characteristic phases of a DO event. The spatial pattern of the warming and the delayed reaction in Antarctica in our model also correlate well with the actual data.

What this theory lacks is a trigger: what caused such disruptions in the Nordic Seas? The Greenland ice core data indicate that a mysterious cycle lasting 1,470 years underlies these events, which was discovered by Gerard Bond and is also found in other climate data. The interval between successive DO events is very often exactly 1,470 years, sometimes also two or three times that value, as if there were some kind of regular oscillation which triggers a DO event sometimes, but not every time. Our model calculations show how the instability of Atlantic currents can act as a huge non-linear amplifier, transforming an originally weak cycle into a dramatic and abrupt climate change. The irregular sequence of DO events can be reproduced well in the model if it is assumed to be triggered by a weak 1,470-year oscillation in combination with random fluctuations (e.g. weather variability). In that case, the climate changes are triggered by a phenomenon which physicists call "stochastic resonance". The only problem is that there is no known cycle of such duration which could act as a trigger. But perhaps we are seeing a superposition of cycles: the two well-known cycles of solar activity, the Gleissberg cycle (period: 87 years) and the De-Vries cycle (period: 210 years), just happen to have a period of 1,470 years as their lowest common multiple. In our climate model, DO events can indeed be triggered

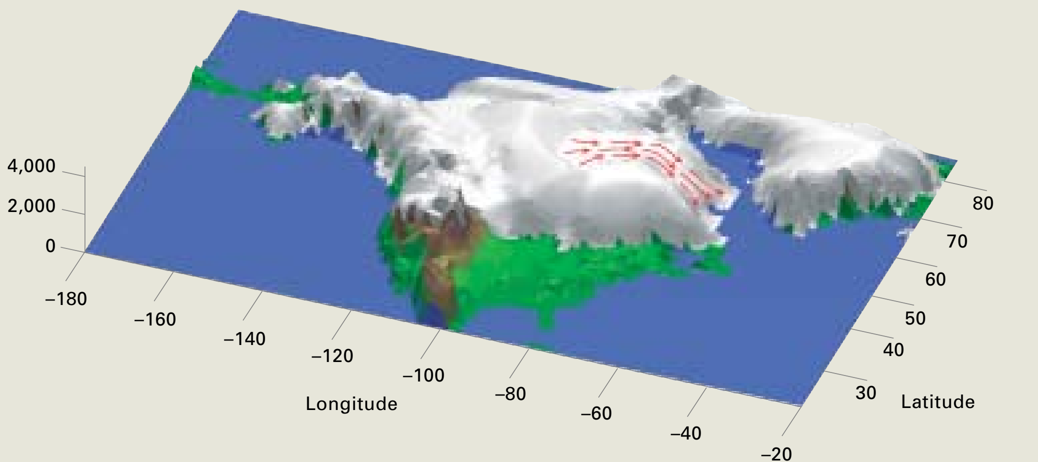
Fig. 3 Timing of Dansgaard-Oeschger events



Source: Ganopolski and Rahmstorf, 2001

This graph shows the characteristic temperature evolution of a number of Dansgaard-Oeschger events derived from Greenland ice core data (coloured lines) and a model simulation (black line). An abrupt rise in temperature can clearly be seen at the beginning of each event. It is followed by a plateau phase with a warm temperature and a slight downward trend (in the model, due to the gradual weakening of the warm ocean current). In the third phase, the temperature drops relatively quickly back to the cold original level. In the model, this occurs when the current abruptly ceases to flow into the Nordic Seas.

Fig. 4 Ice cover on the North American continent



Source: Potsdam Institute for Climate Impact Research

A Heinrich event in a model simulation by PIK. The illustration shows a snapshot of the ice cap on the North American continent simulated by the model. Part of the ice has just slipped off into the Labrador Sea to the east. Such Heinrich events occurred repeatedly during the last ice age.

at this interval by combining these two cycles. Further research is needed to substantiate or refute these still speculative theories.

DO events are not the only abrupt climate changes found in recent climate history. So-called Heinrich events (Fig. 4) occurred at irregular intervals of several thousand years during the last ice age. These events can be seen in deep-sea sediments from the North Atlantic, where each such event left an up to one metre thick layer of small stones instead of the usual soft sediment. These stones are too heavy to have been transported by the wind or ocean currents – they can only have dropped to the sea bed from melting icebergs. Great armadas of icebergs must have drifted across the Atlantic at certain times. These are assumed to have broken off the North American continental ice sheet and entered the ocean through Hudson Strait. They were probably caused by an instability in the ice sheet, which was several thousand metres thick at the time. Snowfall caused it to grow continually until the slopes became unstable and slipped – rather like a mound of sand from which the sand slides down in avalanches as more sand is piled on top.

Sediment data indicate that the formation of North Atlantic Deep Water (NADW) temporarily ceased completely as a result of the Heinrich events. This is shown by the upper circulation mode in Fig. 2. Climate data reveal an associated, abrupt drop in temperature, particularly in the mid-latitudes, e.g. the Mediterranean region. Greenland was affected to a lesser extent, probably because in glacial times the warm current did not reach far enough to the north to warm the climate at higher latitudes (except during DO events).

One important question is why the climate in our present interglacial period (the Holocene) is evidently more stable than the climate of the last ice age. There have not been any DO events or Heinrich events during the Holocene, i.e. for more than 10,000 years. One final, but fairly weak, phase of abrupt cooling occurred 8,200 years ago (sometimes referred to as the 8k event – Fig. 1). Data and simulations indicate that it resulted from the last inflow of meltwater at the end of the ice age. When the dam of ice holding back the huge meltwater lake known as Lake Agassiz broke, the freshwater poured into the Atlantic and temporarily disturbed the warm North Atlantic Current. Many researchers believe that it was the relatively stable climate of the Holocene that prompted man to start farming and settle some 10,000 years ago.

The reason why there have been no Heinrich events during the Holocene is self-evident: they can only occur during an ice age because they are due to instabilities in the continental ice sheets. The answer is more complex in the case of DO events. If our theory of DO events as outlined above is correct, it would be the different ocean circulation mode prevailing in the Atlantic that makes the Holocene climate so stable. This circulation mode is not right near a threshold like the circulation mode during the ice age, and it cannot be disrupted by minor disturbances. This also applies in the computerised climate model: the disturbances with which we triggered DO events under ice age conditions have no effect on the model climate under the conditions of the Holocene. Our calculations indicate that considerably greater disturbances would be needed to disrupt today's Atlantic currents.

This gives rise to the question whether man could upset the climate system to such an extent as to trigger another abrupt climate change. This can be neither affirmed nor ruled out at present, nor will it be possible to make firm predictions in the foreseeable future. Global warming will probably weaken the formation of deep water in the Atlantic, because the ocean water in critical regions is diluted by increased atmospheric freshwater transport and by water from melting ice – this is already evident from observational data. The question whether or when a critical threshold might be crossed and cause the current to cease completely is considerably more difficult to answer. Too much depends on regional circumstances which cannot be resolved by today's models, as well as on such uncertain forcing factors as the inflow of meltwater from Greenland. Models can therefore provide no more than a rough indication.

Regardless of how well we can already explain the mechanisms of climate change with our present understanding and computer models, the Greenland ice contains a clear warning: the climate system is by no means a sluggish, good-natured sloth – it can react very abruptly and violently.

In view of the uncertainty, what is needed is a risk assessment rather than predictions of abrupt climate change – rather like assessing the risks of a nuclear accident. Abrupt climate changes could be considered "accidents" in climate change. In addition to the risk of a sudden change in ocean currents, there are other risks which must be considered – such as the risk of the West Antarctic Ice Sheet disintegrating due to global warming (raising the sea level by several metres), or the monsoon circulation changing, or large areas of rainforest drying out. Although the probability of such "climate accidents" is fortunately not very high, the risks need to be investigated in more detail. Last but not least, we also need a broad public debate over what level of risk of abrupt climate change is considered acceptable. That is a question which cannot be answered by science alone.

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After studying physics at the Universities of Ulm and Konstanz and physical oceanography at the University of Wales (Bangor), Stefan Rahmstorf completed a thesis on general relativity theory. He then moved to New Zealand and obtained his PhD in oceanography at Victoria University of Wellington in 1990, which involved a number of research cruises in the South Pacific.

He continued his research at the New Zealand Oceanographic Institute, at the Institute of Marine Science in Kiel, and since 1996 at the Potsdam Institute for Climate Impact Research. His work focuses on the role of ocean currents in climate change.

In 1999, he received a US$-1m fellowship award from the US-based James S. McDonnell Foundation. He has been teaching physics of the oceans as a professor at Potsdam University since 2000. Rahmstorf is a member of the NOAA Panel on Abrupt Climate Change and of the advisory board on sustainable development of the state of Baden-Württemberg.