

CLIMATE CHANGE

Did You Say “Fast”?

Jacqueline Flückiger

When Manhattan froze in a day in the movie *The Day After Tomorrow* as a result of an abrupt change in the Atlantic meridional overturning circulation, scientists emphasized the physical impossibility of this scenario. Now some might be stunned by how quickly climate can change. On page 680 of this issue, Steffensen *et al.* (1) zoom in on three climatic shifts recorded in the NGRIP ice core from central Greenland (see the photo) (2) and show that the atmospheric circulation at mid to high northern latitudes changed within just 1 to 3 years.

The authors study the onset of the Bølling-Allerød warm period (~14,700 years ago) and the onset (~12,850 years ago) and



How climate shifts. The ice core drilled at NGRIP in central Greenland revealed rapid climatic shifts in the past. Steffensen *et al.* now report a multiproxy analysis of the ice that sheds detailed light on their timing and mechanisms.

termination (~11,700 years ago) of the Younger Dryas cold period. For each shift, they present reconstructions with subannual resolution of $\delta^{18}\text{O}$ (a proxy for local temperature), deuterium excess (a proxy for ocean surface temperature at the source region of the NGRIP precipitation), dust and calcium (originating from low-latitude Asian deserts), sodium (a marine sea salt indicator), and local accumulation rates. The high resolution of the records allows them to precisely define the duration of the shifts, and because all measurements were done along the same ice core, the sequence of events in different prox-

ies can be compared without uncertainty in the relative timing.

The surprising result is that the deuterium excess shifts within 1 to 3 years. The authors interpret the deuterium excess data as a reorganization of the atmospheric circulation in mid to high northern latitudes, leading to a spatial shift in the source region and, therefore, the source temperature of the precipitation. The deuterium excess shift happens very early, whereas the other records continue to change gradually over the subsequent 50 to 150 years.

Generally, abrupt climatic events such as those studied by Steffensen *et al.* are associated with changes in the strength of the Atlantic meridional overturning circulation (3). Steffensen *et al.* hypothesize that additionally, the Northern Hemisphere atmospheric circulation had a very sensitive threshold, which led to the observed fast reorganization. The slower changes found in Greenland temperature and dust might be dominated by the effects of the slower changing ocean circulation and its far-field effects.

Are these ice-core results supported by other paleorecords? A reorganization of the atmospheric circulation implies changes in wind fields, which will affect paleo-archives sensitive to wind-driven upwelling. Examples in the North Atlantic region are varved sediments from lakes (4) and laminated marine deposits such as those from the Cariaco Basin (5). So far, the resolution of the published records from these archives is insufficient to conclude that changes happened within just a few years, but annual resolution is within reach.

A reorganization of the atmospheric circulation may also influence the monsoon systems. Speleothems in Asia have revealed precipitation shifts lasting only a decade at the end of the Younger Dryas (6). In the hunt for annually resolved speleothems, Treble *et al.* (7) found one very abrupt shift 16,070 years ago, lasting only a few years. They hypothesize that the event is related to a reorganization of the

Greenland ice-core data show that large climatic shifts can occur within just 1 to 3 years.

atmospheric circulation during Heinrich event 1, a strong ice discharge event in the North Atlantic. Although Heinrich events are usually not seen in Greenland ice cores, it may be worth searching for an abrupt deuterium excess shift, especially because the low-resolution deuterium-excess record measured along the GRIP ice core shows a substantial change around the same time (8).

But rapid change is not the whole story. For the onset of the Bølling-Allerød and the termination of the Younger Dryas, Steffensen *et al.* find that the dust starts to decrease about a decade before the rapid deuterium-excess shift. This implies that the precipitation in Asia intensified before the reorganization of the atmospheric circulation at mid- to high latitudes. The first sign of climatic change may thus originate from Asia and not from the North Atlantic region.

Other records also show precursor events to the North Atlantic changes. One example is the atmospheric N_2O record measured along the GRIP and NGRIP ice cores for a series of warm events—called Dansgaard-Oeschger events—that were similar to the Bølling-Allerød but took place during the last glacial period. The N_2O concentration variations resemble the pattern of Northern Hemisphere climate events, but the N_2O concentration starts to rise a few centuries before the Greenland warming (9). Early changes for the same events are also found in intermediate-water-temperature tracers measured along a marine core from the Santa Barbara Basin (10). These records indicate that parts of the climate system started to move toward a new state before the abrupt transition in the North Atlantic.

Global coupled climate models provide one way to study the complex mechanisms that underlie climate shifts. Simulated climate shifts are, however, considerably slower than the observed ones, lasting a hundred to a few hundred years (11, 12). This might be due to missing feedbacks, the wrong forcing of the abrupt shifts, or a misguided focus on changes in ocean circulation or temperature, rather than other aspects of the climate system. A closer look at wind patterns and atmospheric circulation in models will either reveal faster shifts and help clarify the underlying mechanisms, or tell us that better models are needed to study that question.

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We should keep in mind that we only know the relative timing for three events so far, and that each of them looks somewhat different (*I*). Greenland ice cores offer the opportunity to study the 24 Dansgaard-Oeschger events of the last glacial period at a similar resolution. The data from all events, in combination with annually resolved records from other archives and improved models, will help to elucidate the dynamics of these events, revealing what they have in common, and what parts of the shifts are random.

The data reported by Steffensen *et al.* underscore the fact that the atmospheric circulation may shift from one state to another within just 1 year. With ongoing global warming, the climate system might therefore hold some surprises.

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MATERIALS SCIENCE

Electrochemical Capacitors for Energy Management

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Energy storage technology is a key element in harvesting the kinetic energy that is wasted whenever vehicles or large machines must be slowed or stopped. Although batteries have been successfully used in light-duty vehicles, hybrid platforms for trucks and buses will require storage and delivery of much higher currents than can be accommodated readily by batteries. Unlike batteries, electrochemical capacitors (ECs) can operate at high charge and discharge rates over an almost unlimited number of cycles and enable energy recovery in heavier-duty systems.

Like all capacitors, ECs (also called supercapacitors or ultracapacitors because of their extraordinarily high capacitance density) physically store charge. Conventional electrostatic and electrolytic capacitors store charge on low-surface-area plates, but ECs store charge in an electric double layer set up by ions at the interface between a high-surface-area carbon electrode and a liquid electrolyte (*1, 2*). ECs first appeared on the market in 1978 as farad-sized devices to provide computer memory backup power.

A simple EC can be constructed by inserting two conducting rods in a beaker of salt water. During charging, charge separation occurs at each liquid-solid interface and potential builds up between the rods. Solvated ions in the electrolyte are rapidly attracted to the solid surface by an equal but

opposite charge in the solid. These two parallel regions of charge are the source of the term “double layer.” This process in effect creates two capacitors, connected in series by the electrolyte, that stay charged after the circuit is opened. Because the surface area of activated carbon electrode material can be thousands of square meters per gram, a 5000-farad EC (a million times the capacitance offered by typical electrostatic or electrolytic capacitors) can be small enough to be handheld.

This very high capacitance comes at a cost: The operating voltage of an EC cannot exceed the potential at which the electrolyte undergoes chemical reactions (typically 1 to 3 V per cell). For high-voltage applications, EC cells, like batteries, can be series-connected.

One of the most important advantages of batteries over ECs is that for a given volume, they can store 3 to 30 times more charge. However, ECs can deliver hundreds to many thousands of times the power of a similar-sized battery. In addition,

Rapid storage and efficient delivery of electrical energy in heavy-duty applications are being enabled by electrochemical capacitors.



ECs at work. Hybrid diesel/electric rubber-tired gantry crane with DLCAP electrochemical capacitor energy storage system (fuel savings of 40% are typical).

Property	Battery	Electrochemical capacitor
Storage mechanism	Chemical	Physical
Power limitation	Reaction kinetics, mass transport	Electrolyte conductivity
Energy storage	High (bulk)	Limited (surface area)
Charge rate	Kinetically limited	High, same as discharge rate
Cycle life limitations	Mechanical stability, chemical reversibility	Side reactions

Comparison of properties of rechargeable batteries and electrochemical capacitors.

the highly reversible electrostatic charge storage in ECs does not produce the changes in volume that usually accompany the redox reactions of the active masses in batteries. Such volume changes are the main cause of

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