The Science of Abrupt Climate Change

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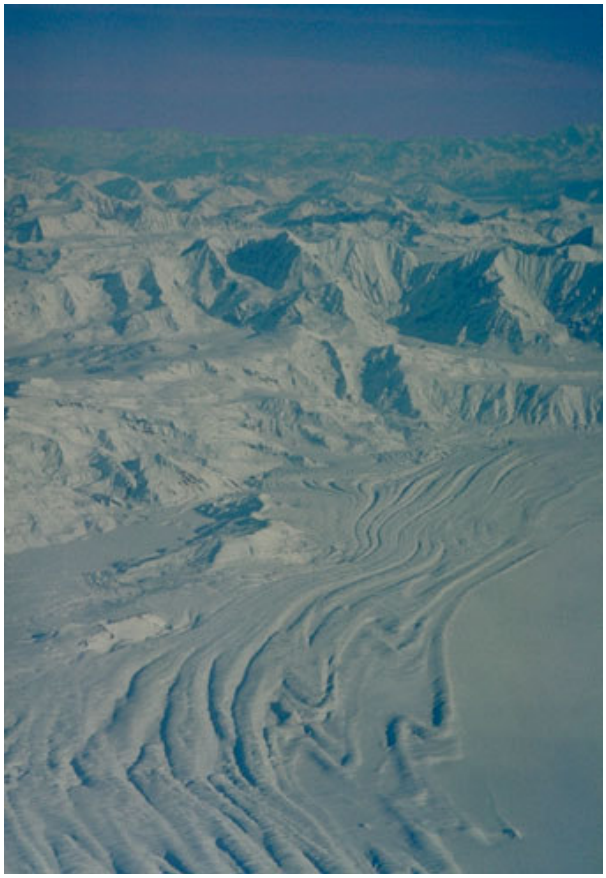
Introduction

In the debate on climate change, we are used to hearing about climate changes on the scale of hundreds or even thousands of years. But since the early 1990s, a radical shift in the scientific understanding of Earth's climate history has occurred. We now know that that major regional and global climate shifts as recently as 8200 years ago have occurred in just a few decades or even a single year. If an abrupt climate change of similar magnitude happened today, it would have severe consequences for humans and natural ecosystems. Although scientists consider an abrupt climate change unlikely in the next 100 years, they concede that their understanding of the phenomena is so incomplete that such a change could be triggered at any time by natural processes or by human-caused global warming.

The National Academy of Sciences--the board of scientists established by Congress in 1863 to advise the federal government on scientific matters--compiled a comprehensive report in 2002 entitled, Abrupt Climate Change: Inevitable Surprises. The 244-page report, which contains over 500 references, was written by a team of 59 of the top researchers in climate, and represents the most authoritative source of information about abrupt climate change available. Unless noted otherwise, all of the material that follows was taken from this report.



The Greenland Ice Sheet: The Key to Understanding Earth's Climate

Ice cores hold a amazingly detailed record of Earth's climate. Each year, snow falling on glacial areas accumulates, piling on top of thousands of years of past snow, compressing the snow into yearly layers of ice, like rings inside a tree trunk. Preserved in the ice are tiny bubbles of ancient air that tell us the composition of the atmosphere at that time. The amount of dust in the snow tells us how windy the climate was. The thickness of the layer tells how much precipitation fell that year. Most importantly, the amount of the "heavy" isotope of oxygen, $_{18}O$, lets us infer the average atmospheric temperature, since water vapor with "heavy" $_{18}O$ molecules condenses out of clouds more readily at cold temperatures.

Accessing this treasure-trove of climatic information is a huge undertaking--cores of ice must be drilled miles deep in some of the most inhospitable places on Earth. In 1989 the National Science Foundation funded the $25 million Greenland Ice

Sheet Project II (GISP2) to drill an ice core through the entire two mile depth of the Greenland ice sheet. At the same time, a separate European project (GRIP), drilled through the ice just 20 miles away, providing a crucial independent check of the GISP2 data. By 1993, both the GRIP and GISP2 drills had hit bedrock, and two miles of ice cores, preserving 110,000 years of climate history in year-by-year layers, were taken to laboratories for analysis.

What the scientists found was surprising and unnerving. Scientists had known from previous ice core and ocean sediment core data that Earth's climate had fluctuated significantly in the past. But what astonished scientists was the rapidity with which these changes occurred. As seen in Figure 1, the ice core record showed *frequent* sudden warmings and coolings of 15°F (8°C) or more. Many of these changes happened in less than 10 years. And in at least one case 11,600 years ago, when Earth emerged from the final phase of the most recent ice age (an event called the Younger Dryas), the Greenland ice core data showed that a 15°F (8°C) warming occurred in less than a decade, accompanied by a doubling of snow accumulation in 3 years. Most of this doubling occurred in *a single year*.

Ocean and lake sediment data from places such as California, Venezuela, and Antarctica have confirmed that these sudden climate changes affected not just Greenland, but the entire world. And during the past 110,000 years, there have been at least 20 such abrupt climate changes. Only one period of stable climate has existed during the past 110,000 years--the 11,000 years of modern climate (the "Holocene" era). "Normal" climate for Earth is the climate of sudden extreme jumps--like a light switch flicking on and off.

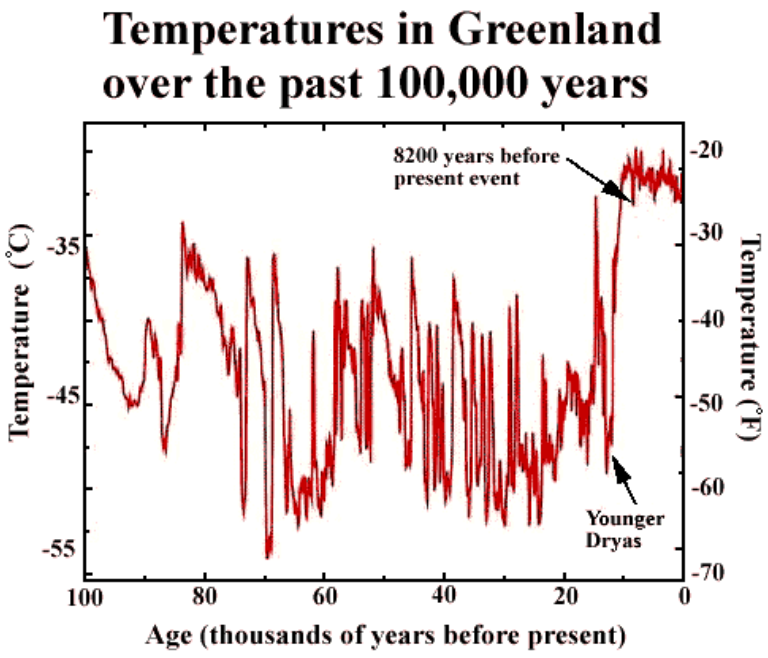


Figure 1. Average yearly temperatures in Greenland over the past 100,000 years as inferred from oxygen isotope analysis of the GISP2 Greenland ice core. **Source:** Cuffey, K.M., and G.D. Clow, "Temperature, accumulation, and ice sheet elevation in central Greenland throughout the last deglacial transition", *Journal of Geophysical Research*, **102**, 383-396, 1997.

What causes abrupt climate change?

Current theories on abrupt climate change focus on sudden shut downs and start-ups of the Gulf Stream ocean current in the North Atlantic as the most likely cause. The Gulf Stream transports a tremendous amount of heat northward, keeping the North Atlantic and much of Europe up to 9°F (5°C) warmer, particularly in the winter. A sudden shut down of the Gulf Stream would have a ripple effect throughout the ocean-atmosphere system, forcing worldwide changes in ocean currents and in the path of the atmospheric jet stream. Studies of

North Atlantic Ocean sediments have revealed that the Gulf Stream has shut down many times in the past, and that many of these shut downs coincide with the abrupt climate change events noted in the Greenland ice cores.

How does one shut down the Gulf Stream? To answer this, we first must describe the Great Ocean Conveyor Belt (Figure 2), the system of interconnected ocean currents that girdle the planet. At the surface, ocean currents are driven by the winds, and so move parallel to the wind direction, except where continental land masses block the way. Water can also move vertically in the ocean. High density water sinks, and low density water rises. Salty water is more dense than fresh water, and cold water is more dense than warm water, so that wherever we find cold, salty water, it tends to sink.

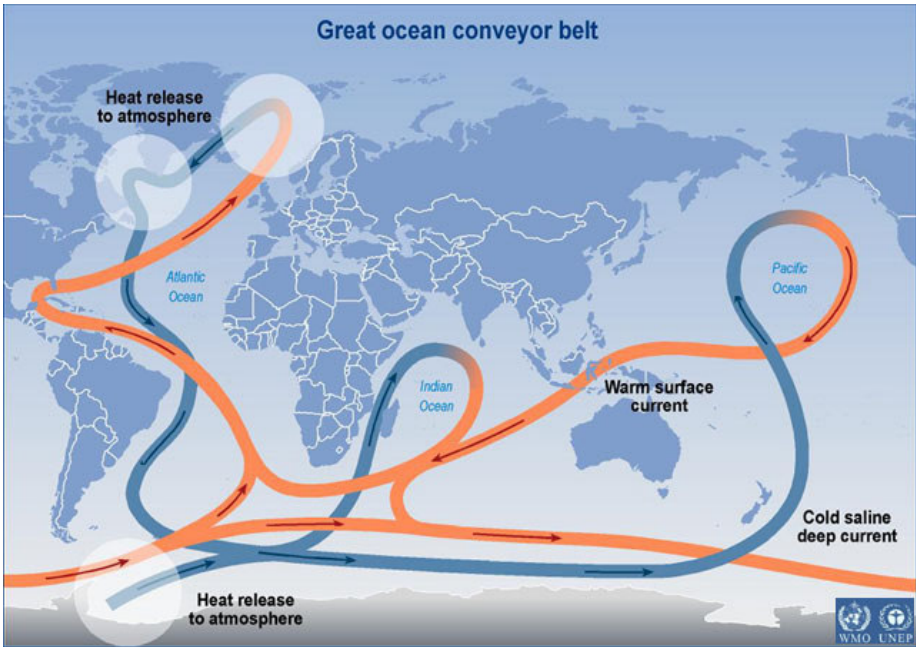


Figure 2. The Great Ocean Conveyor Belt consists of an interconnected network of warm surface currents (shown in orange) and cold deep water currents (shown in blue). Warm, salty, surface waters lose their heat to the atmosphere in the areas labeled "Heat loss to atmosphere" and sink to the bottom of the ocean. **Source:** Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2001: The Scientific Basis"

In the tropical Atlantic, the sun's heat evaporates large amounts of water, creating relatively warm, salty ocean water. This warm, salty water flows westward toward North America, then up the East Coast of the U.S., then northeastward toward Europe, forming the mighty Gulf Stream current. As this warm, salty water reaches the ocean regions on either side of Greenland, cold winds blowing off of Canada and Greenland cool the water substantially (in Figure 2, these regions are marked with white circles labeled, "Heat release to the atmosphere.") These cool, salty waters are now very dense compared to the surrounding waters, and sink to the bottom of the ocean. Thus, the oceanic areas by Greenland where this sinking occurs are called "deep-water formation areas". This North Atlantic deep water flows southward toward Antarctica, eventually making it all the way to the Pacific Ocean, where it rises back to the surface to complete the Great Ocean Conveyor Belt. It takes about 1000 years for the water to make a complete circuit around the globe.

Since the Great Ocean Conveyor belt is driven in part by differences in ocean water density, if one can pump enough fresh water into the ocean in the key areas on either side of Greenland where the Gulf Stream waters cool and sink, this will lower the ocean's salinity (and therefore its density) enough so that the waters there no longer sink. The Atlantic conveyor belt and Gulf Stream current

will then shut down in just a few years, dramatically altering the climate.

The key question remains: how much fresh water is needed to shut down the Atlantic conveyor belt? No one knows the answer. Scientists are pretty sure that the last two abrupt coolings seen the the Greenland ice core, the "Younger Dryas" event and the "8200 years before present" event (Figure 1), both occurred when huge North American glacial melt-water lakes flooded down the St. Lawrence River into the North Atlantic when the ice dams restraining the lakes broke. The sudden addition of low-density fresh water presumably partially or totally stopped the sinking of ocean waters in the North Atlantic, slowing or completely stopping the Gulf Stream current. Once the fresh water got into the North Atlantic, it stayed, puddling on top of the ocean and freezing in winter. The Gulf Stream stayed shut off for about 1100 years during the Younger Dryas event, then suddenly restarted, for reasons scientists don't understand. Current computer models of the climate cannot reproduce the observed sudden shut-down or start-up of the Gulf Stream at the beginning and end of the Younger Dryas period.

Other sudden shut downs of the Gulf Stream observed in ice core and ocean sediment records are not thought to be due to sudden melt-water floods into the North Atlantic. These events may have happened simply because Earth's climate system is chaotic, or perhaps because some critical threshold was crossed when increases in precipitation, river run-off, and ice melt put enough fresh water into the ocean to shut down the Gulf Stream.

How likely is it that global warming will trigger abrupt climate change?

Global warming will increase precipitation, river run-off, melting of the Greenland ice sheet, and melting of polar sea ice, all of which will increase the amount of fresh water flowing into the critical deep-water formation areas by Greenland. Current scientific thinking is that global warming will not trigger abrupt climate change in the next 100 years. Most climate models used to study this problem show a slowing of the Gulf Stream current of 20% - 50% over the next century; a full shutdown of the Gulf Stream would take a relatively extreme 9°F (5°C) warming of the climate, which is not expected to happen this century. One climate model suggests that global warming will not slow down the Gulf Stream at all, since a warmer world will increase evaporation from the Atlantic Ocean, making it saltier and thus more resistant to fresh water interruption of the deep water formation near Greenland. However, none of these computer models of the atmosphere and ocean can duplicate the sudden climate changes observed in the Greenland ice core. Scientists admit that it is possible that Earth's climate may suddenly cross the critical threshold needed to trigger abrupt climate change at any time, and that the extra "forcing" humans apply to the climate system by emitting large amounts of greenhouse gases into the atmosphere makes this possibility far more likely than it would be otherwise.

Is there evidence that abrupt climate change may happen soon?

Measurements taken in the North Atlantic Ocean show a substantial decrease in salinity over the past 30 years. This has happened in response to the additional fresh water inputs to the system from three sources, all of which may be partially due to global warming:
Precipitation and river run-off have increased 7% - 12% in the area between 30°N and 85°N latitude in the past 100 years. Higher temperatures in the Arctic have caused a 40% thinning of the polar sea ice in the past 40 years, based on measurements from submarines. The Greenland ice sheet has been melting at a rate equivalent to a .13 mm/year increase in global sea level.

However, long term measurements of the strength of the Gulf Stream circulation, particularly in the deep ocean, are virtually non-existent, and it is simply not known if the recent increase in fresh water to the Arctic may be close to triggering a shut down of the Gulf Stream.

How would the climate change if the Gulf Stream shut down?

A shut down of the Gulf Stream would suddenly decrease the amount of heat in the North Atlantic, leading to much colder temperatures in Europe and North America. A 2003 report prepared for the Department of Defense outlines what would happen if an abrupt climatic change similar to the 8200 years before present event were to recur today:
Annual average temperatures would drop up to 5°F in North America, and up to 6°F in northern Europe. This is not sufficient to trigger an ice age, which requires about a 10°F drop in temperature world-wide, but could bring about conditions like experienced in 1816--the famed "year without a summer". In that year, volcanic ash from the mighty Tambora volcanic eruption in Indonesia blocked the sun's rays, significantly cooling the globe. Snow fell in New England in June, and killing frosts in July and August caused widespread crop failures and famine in New England and northern Europe. Annual average temperatures would warm up to 4°F in many areas of the Southern Hemisphere. Multi-year droughts in regions unaccustomed to drought would affect critical agricultural and water resource regions world-wide, greatly straining food and water supplies. Winter storms and winds would strengthen over North America and Europe.

Dr. Wally Broecker of Columbia University, the scientist who first pointed out the link between the Atlantic's conveyor circulation and abrupt climate change, wrote a letter in March 2004 to *Science* magazine, accusing the authors of the study of making exaggerated claims that "only intensify the existing polarization over global warming". Broecker argued that a global-warming induced abrupt climate change is not likely to occur until 100 years or so into the future, by which time Earth's temperature will have warmed sufficiently to offset much of the abrupt cooling a Gulf Stream shut down would trigger. Broecker added: "What is needed is not more words but rather a means to shut down carbon dioxide emissions." The authors of the study defend their scenario thusly: "We have created a climate change scenario that although not the likely, is plausible, and would challenge United States national security in ways that should be considered immediately".

What is being done about abrupt climate change?

The immediate obvious needs are for accurate, long-term measurements of the temperature, salinity, and flow rates of the major ocean currents in the North Atlantic Ocean. An expedition set sail from Great Britain on Feb. 13 2004, to provide just that. The voyage is part of a joint US/UK research project called Rapid Climate Change, which began in 2001. In the U.S., Senator Susan Collins (R-Maine) sponsored bill S.1164 to authorize $60 million for the National Oceanic and Atmospheric Administration (NOAA) to study abrupt climate change. On March 9, 2004, the Senate Commerce Committee approved the bill. It defines abrupt climate change as "a change in the climate that occurs so rapidly or unexpectedly that human or natural systems have difficulty adapting to the climate as changed." The bill would create a research program within NOAA's Office of Oceanic and Atmospheric Research to determine what causes sudden climate changes and using computer models to predict climate change events.

Conclusion

The historical records shows us that abrupt climate change is not only possible--it is the normal state of affairs. The present warm, stable climate is a rare anomaly. It behooves us to learn as much as we can about the climate system so that we may be able to predict when the next abrupt shift in climate will come. Until we know better when this might happen, it would be wise to stop pouring so much carbon dioxide into the air. A nasty surprise might be lurking just around the corner. In the words of Dr. Wally Broecker, "the climate system is an angry beast, and we are poking it."

For further reading:

NASA's "A Chilling Possibility" press release, March 2004.
Abrupt Climate Change: Should we be worried?" Analysis by Woods Hole Oceanographical Institute, January 2003.
The Great Climate Flip-flop, a 1998 *Atlantic Monthly* article.
Abrupt climate change, a report prepared by Global Business Network (GBN) for the Department of Defense, October 2003.

The Two-Mile Time Machine : Ice Cores, Abrupt Climate Change, and Our Future, by Dr. Richard Alley, 2001. An excellent book on the Greenland ice cores findings.

Skeptics have routinely called global warming "a hoax", and attacked the credibility of scientists promoting the idea. Are the skeptics right? To shed light on the issue, it is helpful to review how the same skeptics treated the ozone hole issue. Read the Weather Underground special feature, *The Skeptics vs. The Ozone Hole.*