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JANUARY 1998

The Great Climate Flip-flop

"Climate change" is popularly understood to mean greenhouse warming, which, it is predicted, will cause flooding, severe windstorms, and killer heat waves. But warming could lead, paradoxically, to drastic cooling -- a catastrophe that could threaten the survival of civilization

by William H. Calvin

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ONE of the most shocking scientific realizations of all time has slowly been dawning on us: the earth's climate does great flip-flops every few thousand years, and with breathtaking speed. We could go back to ice-age temperatures within a decade -- and judging from recent discoveries, an abrupt cooling could be triggered by our current global-warming trend. Europe's climate could become more like Siberia's. Because such a cooling would occur too quickly for us to



make readjustments in agricultural productivity and supply, it would be a potentially civilization-shattering affair, likely to cause an unprecedented population crash. What paleoclimate and oceanography researchers know of the mechanisms underlying such a climate flip suggests that global warming could start one in several different ways.

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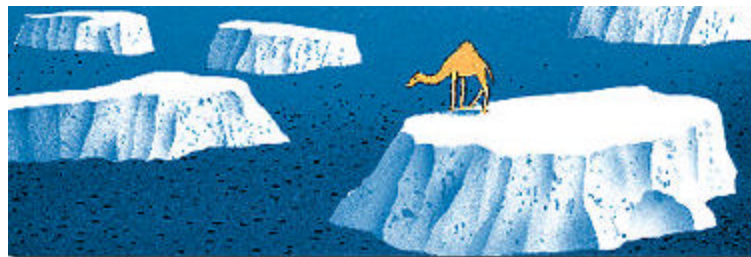
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For a quarter century global-warming theorists have predicted that climate creep is going to occur and that we need to prevent greenhouse gases from warming things up, thereby raising the sea level, destroying habitats, intensifying storms, and forcing agricultural rearrangements. Now we know -- and from an entirely different group of scientists exploring separate lines of reasoning and data -- that the most catastrophic result of global warming could be an abrupt cooling.



We are in a warm period now. Scientists have known for some time that the previous warm period started 130,000 years ago and ended 117,000 years ago, with the return of cold temperatures that led to an ice age. But the ice ages aren't what they used to be. They were formerly thought to be very gradual, with both air temperature and ice

debate is the one between those who say we are rapidly depleting the planet's resources and those who say we will all pull through just fine. The temptation to look for the truth 'somewhere in the middle' may be dangerous folly."

sheets changing in a slow, 100,000-year cycle tied to changes in the earth's orbit around the sun. But our current warm-up, which started about 15,000 years ago, began abruptly, with the temperature rising sharply while most of the ice was still present. We now know that there's nothing "glacially slow" about temperature change: superimposed on the gradual, long-term cycle have been dozens of abrupt warmings and coolings that lasted only centuries.

The back and forth of the ice started 2.5 million years ago, which is also when the ape-sized hominid brain began to develop into a fully human one, four times as large and reorganized for language, music, and chains of inference. Ours is now a brain able to anticipate outcomes well enough to practice ethical behavior, able to head off disasters in the making by extrapolating trends. Our civilizations began to emerge right after the continental ice sheets melted about 10,000 years ago. Civilizations accumulate knowledge, so we now know a lot about what has been going on, what has made us what we are. We puzzle over oddities, such as the climate of Europe.

Keeping Europe Warm

EUROPE is an anomaly. The populous parts of the United States and Canada are mostly between the latitudes of 30° and 45°, whereas the populous parts of Europe are ten to fifteen degrees farther north. "Southerly" Rome lies near the same

latitude, 42°N, as "northerly" Chicago -- and the most northerly major city in Asia is Beijing, near 40° N. London and Paris are close to the 49°N line that, west of the Great Lakes, separates the United States from Canada. Berlin is up at about 52°, Copenhagen and Moscow at about 56°. Oslo is nearly at 60°N, as are Stockholm, Helsinki, and St. Petersburg; continue due east and you'll encounter Anchorage.



Europe's climate, obviously, is not like that of North America or Asia at the same latitudes. For Europe to be as agriculturally productive as it is (it supports more than twice the population of the United States and Canada), all those cold, dry winds that blow eastward across the North Atlantic from Canada must somehow be warmed up. The job is done by warm water flowing north from the tropics, as the eastbound Gulf Stream merges into the North Atlantic Current. This warm water then flows up the Norwegian coast, with a westward branch warming Greenland's tip, at 60°N. It keeps

northern Europe about nine to eighteen degrees warmer in the winter than comparable latitudes elsewhere -- except when it fails. Then not only Europe but also, to everyone's surprise, the rest of the world gets chilled. Tropical swamps decrease their production of methane at the same time that Europe cools, and the Gobi Desert whips much more dust into the air. When this happens, something big, with worldwide connections, must be switching into a new mode of operation.

The North Atlantic Current is certainly something big, with the flow of about a hundred Amazon Rivers. And it sometimes changes its route dramatically, much as a bus route can be truncated into a shorter loop. Its effects are clearly global too, inasmuch as it is part of a long "salt conveyor" current that extends through the southern oceans into the Pacific.

I hope never to see a failure of the northernmost loop of the North Atlantic Current, because the result would be a population crash that would take much of civilization with it, all within a decade. Ways to postpone such a climatic shift are conceivable, however -- old-fashioned dam-and-ditch construction in critical locations might even work. Although we can't do much about everyday weather, we may nonetheless be able to stabilize the climate enough to prevent an abrupt cooling.

Abrupt Temperature Jumps

THE discovery of abrupt climate changes has been spread out over the past fifteen years, and is well known to readers of major scientific journals such as *Science* and *Nature*. The abruptness data are convincing. Within the ice sheets of Greenland are annual layers that provide a record of the gases present in the atmosphere and indicate the changes in air temperature over the past 250,000 years -- the period of the last two major ice ages. By 250,000 years ago *Homo erectus* had died out, after a run of almost two million years. By 125,000 years ago *Homo sapiens* had evolved from our ancestor species -- so the whiplash climate changes of the last ice age affected people much like us.

In Greenland a given year's snowfall is compacted into ice during the ensuing years, trapping air bubbles, and so paleoclimate researchers have been able to glimpse ancient climates in some detail. Water falling as snow on Greenland carries an isotopic "fingerprint" of what the temperature was like en route. Counting those tree-ring-like layers in the ice cores shows that cooling came on as quickly as droughts. Indeed, were another climate flip to begin next year, we'd probably complain first about the drought, along with unusually cold winters in Europe. In the first few years the climate could cool as much as it did during the misnamed Little Ice Age (a gradual cooling that lasted from the early Renaissance until the end of the nineteenth

century), with tenfold greater changes over the next decade or two.

The most recent big cooling started about 12,700 years ago, right in the midst of our last global warming. This cold period, known as the Younger Dryas, is named for the pollen of a tundra flower that turned up in a lake bed in Denmark when it shouldn't have. Things had been warming up, and half the ice sheets covering Europe and Canada had already melted. The return to ice-age temperatures lasted 1,300 years. Then, about 11,400 years ago, things suddenly warmed up again, and the earliest agricultural villages were established in the Middle East. An abrupt cooling got started 8,200 years ago, but it aborted within a century, and the temperature changes since then have been gradual in comparison. Indeed, we've had an unprecedented period of climate stability.

Coring old lake beds and examining the types of pollen trapped in sediment layers led to the discovery, early in the twentieth century, of the Younger Dryas. Pollen cores are still a primary means of seeing what regional climates were doing, even though they suffer from poorer resolution than ice cores (worms churn the sediment, obscuring records of all but the longest-lasting temperature changes). When the ice cores demonstrated the abrupt onset of the Younger Dryas, researchers wanted to know how widespread this event was. The U.S. Geological Survey took old lake-bed cores

out of storage and re-examined them.

Ancient lakes near the Pacific coast of the United States, it turned out, show a shift to cold-weather plant species at roughly the time when the Younger Dryas was changing German pine forests into scrublands like those of modern Siberia. Subarctic ocean currents were reaching the southern California coastline, and Santa Barbara must have been as cold as Juneau is now. (But the regional record is poorly understood, and I know at least one reason why. These days when one goes to hear a talk on ancient climates of North America, one is likely to learn that the speaker was forced into early retirement from the U.S. Geological Survey by budget cuts. Rather than a vigorous program of studying regional climatic change, we see the shortsighted preaching of cheaper government at any cost.)

In 1984, when I first heard about the startling news from the ice cores, the implications were unclear -- there seemed to be other ways of interpreting the data from Greenland. It was initially hoped that the abrupt warmings and coolings were just an oddity of Greenland's weather -- but they have now been detected on a worldwide scale, and at about the same time. Then it was hoped that the abrupt flips were somehow caused by continental ice sheets, and thus would be unlikely to recur, because we now lack huge ice sheets over Canada and Northern Europe. Though some

abrupt coolings are likely to have been associated with events in the Canadian ice sheet, the abrupt cooling in the previous warm period, 122,000 years ago, which has now been detected even in the tropics, shows that flips are not restricted to icy periods; they can also interrupt warm periods like the present one.

There seems to be no way of escaping the conclusion that global climate flips occur frequently and abruptly. An abrupt cooling could happen now, and the world might not warm up again for a long time: it looks as if the last warm period, having lasted 13,000 years, came to an end with an abrupt, prolonged cooling. That's how our warm period might end too.

Sudden onset, sudden recovery -- this is why I use the word "flip-flop" to describe these climate changes. They are utterly unlike the changes that one would expect from accumulating carbon dioxide or the setting adrift of ice shelves from Antarctica. Change arising from some sources, such as volcanic eruptions, can be abrupt -- but the climate doesn't flip back just as quickly centuries later.

Temperature records suggest that there is some grand mechanism underlying all of this, and that it has two major states. Again, the difference between them amounts to nine to eighteen degrees -- a range that may depend on how much ice there is to slow the responses. I call the colder one the "low

state." In discussing the ice ages there is a tendency to think of warm as good -- and therefore of warming as better. Alas, further warming might well kick us out of the "high state." It's the high state that's good, and we may need to help prevent any sudden transition to the cold low state.

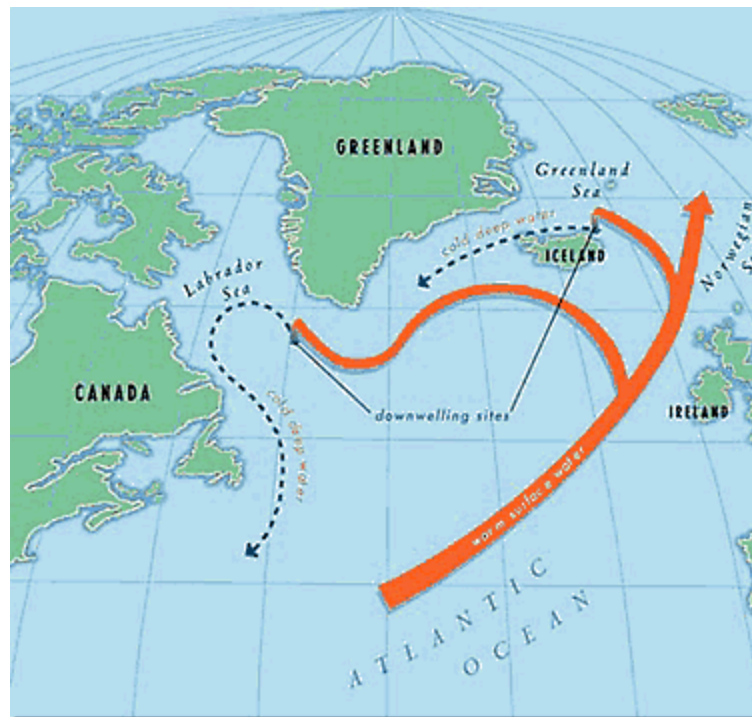
Although the sun's energy output does flicker slightly, the likeliest reason for these abrupt flips is an intermittent problem in the North Atlantic Ocean, one that seems to trigger a major rearrangement of atmospheric circulation. North-south ocean currents help to redistribute equatorial heat into the temperate zones, supplementing the heat transfer by winds. When the warm currents penetrate farther than usual into the northern seas, they help to melt the sea ice that is reflecting a lot of sunlight back into space, and so the earth becomes warmer. Eventually that helps to melt ice sheets elsewhere.

The high state of climate seems to involve ocean currents that deliver an extraordinary amount of heat to the vicinity of Iceland and Norway. Like bus routes or conveyor belts, ocean currents must have a return loop. Unlike most ocean currents, the North Atlantic Current has a return loop that runs deep beneath the ocean surface. Huge amounts of seawater sink at known downwelling sites every winter, with the water heading south when it reaches the bottom. When that annual flushing fails for some years, the conveyor belt stops moving

and so heat stops flowing so far north -- and apparently we're popped back into the low state.

Flushing Cold Surface Water

SURFACE waters are flushed regularly, even in lakes. Twice a year they sink, carrying their load of atmospheric gases downward. That's because water density changes with temperature. Water is densest at about 39°F (a typical refrigerator setting - - anything that you take out of the refrigerator, whether you place it on the kitchen counter or move it to the freezer, is going to expand a little). A lake surface cooling down in the autumn will eventually sink into the less-dense-because-warmer waters below, mixing things up. Seawater is more complicated, because salt content also helps to determine whether water floats or sinks. Water that evaporates leaves its salt behind; the resulting saltier water is heavier and thus sinks.



The fact that excess salt is flushed from surface waters has global implications, some of them recognized two centuries ago. Salt circulates, because evaporation up north causes it to sink and be carried south by deep currents. This was posited in 1797 by the Anglo-American physicist Sir Benjamin Thompson (later known, after he moved to Bavaria, as Count Rumford of the Holy Roman Empire), who also posited that, if merely to compensate, there would have to be a warmer northbound current as well. By 1961 the oceanographer Henry Stommel, of the Woods Hole Oceanographic Institution, in Massachusetts, was beginning to worry that these warming currents might stop flowing if too much fresh water was added to the surface of the northern seas. By 1987 the geochemist Wallace Broecker, of Columbia University, was piecing together the

paleoclimatic flip-flops with the salt-circulation story and warning that small nudges to our climate might produce "unpleasant surprises in the greenhouse."

Oceans are not well mixed at any time. Like a half-beaten cake mix, with strands of egg still visible, the ocean has a lot of blobs and streams within it. When there has been a lot of evaporation, surface waters are saltier than usual. Sometimes they sink to considerable depths without mixing. The Mediterranean waters flowing out of the bottom of the Strait of Gibraltar into the Atlantic Ocean are about 10 percent saltier than the ocean's average, and so they sink into the depths of the Atlantic. A nice little Amazon-sized waterfall flows over the ridge that connects Spain with Morocco, 800 feet below the surface of the strait.

Another underwater ridge line stretches from Greenland to Iceland and on to the Faeroe Islands and Scotland. It, too, has a salty waterfall, which pours the hypersaline bottom waters of the Nordic Seas (the Greenland Sea and the Norwegian Sea) south into the lower levels of the North Atlantic Ocean. This salty waterfall is more like thirty Amazon Rivers combined. Why does it exist? The cold, dry winds blowing eastward off Canada evaporate the surface waters of the North Atlantic Current, and leave behind all their salt. In late winter the heavy surface waters sink en masse. These blobs, pushed down by annual repetitions of these late-winter events, flow south, down

near the bottom of the Atlantic. The same thing happens in the Labrador Sea between Canada and the southern tip of Greenland.

Salt sinking on such a grand scale in the Nordic Seas causes warm water to flow much farther north than it might otherwise do. This produces a heat bonus of perhaps 30 percent beyond the heat provided by direct sunlight to these seas, accounting for the mild winters downwind, in northern Europe. It has been called the Nordic Seas heat pump.

Nothing like this happens in the Pacific Ocean, but the Pacific is nonetheless affected, because the sink in the Nordic Seas is part of a vast worldwide salt-conveyor belt. Such a conveyor is needed because the Atlantic is saltier than the Pacific (the Pacific has twice as much water with which to dilute the salt carried in from rivers). The Atlantic would be even saltier if it didn't mix with the Pacific, in long, loopy currents. These carry the North Atlantic's excess salt southward from the bottom of the Atlantic, around the tip of Africa, through the Indian Ocean, and up around the Pacific Ocean.

There used to be a tropical shortcut, an express route from Atlantic to Pacific, but continental drift connected North America to South America about three million years ago, damming up the easy route for disposing of excess salt. The dam, known as the Isthmus of Panama, may have been

what caused the ice ages to begin a short time later, simply because of the forced detour. This major change in ocean circulation, along with a climate that had already been slowly cooling for millions of years, led not only to ice accumulation most of the time but also to climatic instability, with flips every few thousand years or so.

Failures of Flushing

FLYING above the clouds often presents an interesting picture when there are mountains below. Out of the sea of undulating white clouds mountain peaks stick up like islands.

Greenland looks like that, even on a cloudless day -- but the great white mass between the occasional punctuations is an ice sheet. In places this frozen fresh water descends from the highlands in a wavy staircase.

Twenty thousand years ago a similar ice sheet lay atop the Baltic Sea and the land surrounding it. Another sat on Hudson's Bay, and reached as far west as the foothills of the Rocky

Mountains -- where it pushed, head to head, against ice coming down from the Rockies. These northern ice



sheets were as high as Greenland's mountains, obstacles sufficient to force the jet stream to make a detour.

Now only Greenland's ice remains, but the abrupt cooling in the last warm period shows that a flip can occur in situations much like the present one. What could possibly halt the salt-conveyor belt that brings tropical heat so much farther north and limits the formation of ice sheets? Oceanographers are busy studying present-day failures of annual flushing, which give some perspective on the catastrophic failures of the past.

In the Labrador Sea, flushing failed during the 1970s, was strong again by 1990, and is now declining. In the Greenland Sea over the 1980s salt sinking declined by 80 percent. Obviously, local failures can occur without catastrophe -- it's a question of how often and how widespread the failures are -- but the present state of decline is not very reassuring. Large-scale flushing at both those sites is certainly a highly variable process, and perhaps a somewhat fragile one as well. And in the absence of a flushing mechanism to sink cooled surface waters and send them southward in the Atlantic, additional warm waters do not flow as far north to replenish the supply.

There are a few obvious precursors to flushing failure. One is diminished wind chill, when winds aren't as strong as usual, or as cold, or as dry -- as is the case in the

Labrador Sea during the North Atlantic Oscillation. This El Niño-like shift in the atmospheric-circulation pattern over the North Atlantic, from the Azores to Greenland, often lasts a decade. At the same time that the Labrador Sea gets a lessening of the strong winds that aid salt sinking, Europe gets particularly cold winters. It's happening right now: a North Atlantic Oscillation started in 1996.

Another precursor is more floating ice than usual, which reduces the amount of ocean surface exposed to the winds, in turn reducing evaporation. Retained heat eventually melts the ice, in a cycle that recurs about every five years.

Yet another precursor, as Henry Stommel suggested in 1961, would be the addition of fresh water to the ocean surface, diluting the salt-heavy surface waters before they became unstable enough to start sinking. More rain falling in the northern oceans -- exactly what is predicted as a result of global warming -- could stop salt flushing. So could ice carried south out of the Arctic Ocean.

There is also a great deal of unsalted water in Greenland's glaciers, just uphill from the major salt sinks. The last time an abrupt cooling occurred was in the midst of global warming. Many ice sheets had already half melted, dumping a lot of fresh water into the ocean.

A brief, large flood of fresh water might nudge us toward an abrupt cooling even if the dilution were insignificant when averaged over time. The fjords of Greenland offer some dramatic examples of the possibilities for freshwater floods. Fjords are long, narrow canyons, little arms of the sea reaching many miles inland; they were carved by great glaciers when the sea level was lower. Greenland's east coast has a profusion of fjords between 70°N and 80°N, including one that is the world's biggest. If blocked by ice dams, fjords make perfect reservoirs for meltwater.



Glaciers pushing out into the ocean usually break off in chunks. Whole sections of a glacier, lifted up by the tides, may snap off at the "hinge" and become icebergs. But sometimes a glacial surge will act

like an avalanche that blocks a road, as happened when Alaska's Hubbard glacier surged into the Russell fjord in May of 1986. Its snout ran into the opposite side, blocking the fjord with an ice dam. Any meltwater coming in behind the dam stayed there. A lake formed, rising higher and higher -- up to the height of an eight-story building.

Eventually such ice dams break, with

spectacular results. Once the dam is breached, the rushing waters erode an ever wider and deeper path. Thus the entire lake can empty quickly. Five months after the ice dam at the Russell fjord formed, it broke, dumping a cubic mile of fresh water in only twenty-four hours.

The Great Salinity Anomaly, a pool of semi-salty water derived from about 500 times as much unsalted water as that released by Russell Lake, was tracked from 1968 to 1982 as it moved south from Greenland's east coast. In 1970 it arrived in the Labrador Sea, where it prevented the usual salt sinking. By 1971-1972 the semi-salty blob was off Newfoundland. It then crossed the Atlantic and passed near the Shetland Islands around 1976. From there it was carried northward by the warm Norwegian Current, whereupon some of it swung west again to arrive off Greenland's east coast -- where it had started its inch-per-second journey. So freshwater blobs drift, sometimes causing major trouble, and Greenland floods thus have the potential to stop the enormous heat transfer that keeps the North Atlantic Current going strong.

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Illustrations by Guy Billout

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The Atlantic Monthly; January 1998; The Great Climate Flip-Flop; Volume 281, No. 1; pages 47 - 64.

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