THE Atlantic online

The Atlantic Monthly | Digital Edition

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

The online version of this article appears in two parts. Click here to go to part two.

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.

Discuss this article in the Global Views forum of Post & Riposte.

Go to Part Two of this article.

• More *Atlantic* articles looking ahead to the 21st century.

Currently in the December *Atlantic*:

• "No Middle Way on the Environment" by Paul R. Ehrlich, Gretchen C. Daily, Scott C. Daily, Norman Myers, and James Salzman "The oldest environmental

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.

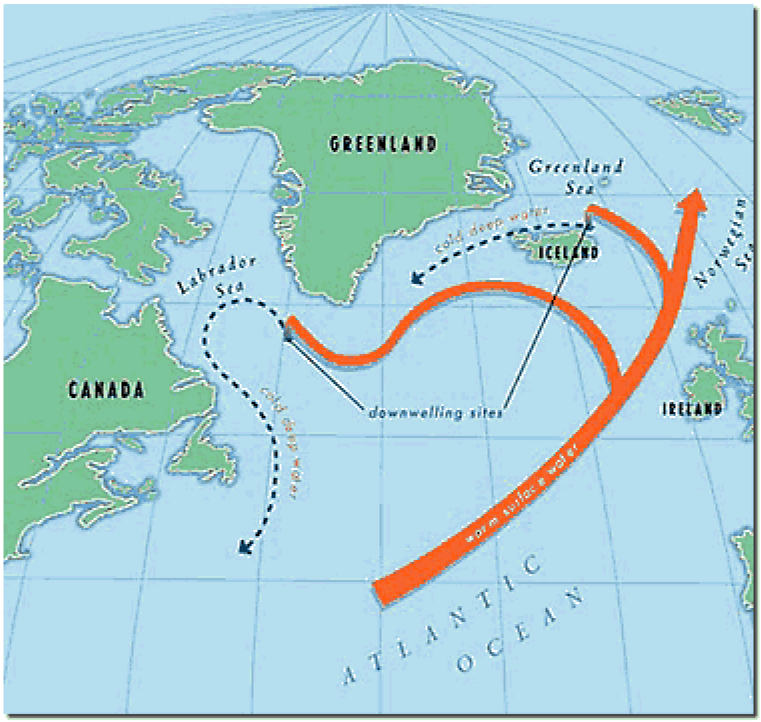
Temperature records suggest that there is some grand mechanism underlying all of this, and that it has two major states. Again, the difference between them amounts to nine to eighteen degrees -- a range that may depend on how much ice there is to slow the responses. I call the colder one the "low state."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

The online version of this article appears in two parts. Click here to go to part two.

William H. Calvin is a theoretical neurophysiologist at the University of Washington at Seattle. For more information on Calvin and his writings, see his personal Web site.

Illustrations by Guy Billout

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

JANUARY 1998

The online version of this article appears in two parts. Click here to go to part one.

The Greenhouse Connection

OF this much we're sure: global climate flip-flops have frequently happened in the past, and they're likely to happen again. It's also clear that sufficient global warming could trigger an abrupt cooling in at least two ways -- by increasing high-latitude rainfall or by melting Greenland's ice, both of which could put enough fresh water into the ocean surface to suppress flushing.

Further investigation might lead to revisions in such mechanistic explanations, but the result of adding fresh water to the ocean surface is pretty standard physics. In almost four decades of subsequent research Henry Stommel's theory has only been enhanced, not seriously challenged.

Up to this point in the story none of the broad conclusions is particularly speculative. But to address how all these nonlinear mechanisms fit together -- and what we might do to stabilize the climate -- will require some speculation.

Even the tropics cool down by about nine degrees during an abrupt cooling, and it is hard to imagine what in the past could have disturbed the whole earth's climate on this scale. We must look at arriving sunlight and departing light and heat, not merely regional shifts on earth, to account for changes in the temperature balance. Increasing amounts of sea ice and clouds could reflect more sunlight back into space, but the geochemist Wallace Broecker suggests that a major greenhouse gas is disturbed by the failure of the salt conveyor, and that this affects the amount of heat retained.

Discuss this article in the Global Views forum of Post & Riposte.

Go to Part One of this article.

In Broecker's view, failures of salt flushing cause a worldwide rearrangement of ocean currents, resulting in -- and this is the speculative part -- less evaporation from the tropics. That, in turn, makes the air drier. Because water vapor is the most powerful greenhouse gas, this decrease in average humidity would cool things globally. Broecker has written, "If you wanted to cool the planet by 5°C [9°F] and could magically alter the water-vapor content of the atmosphere, a 30 percent decrease would do the job."

Just as an El Niño produces a hotter Equator in the Pacific Ocean and generates more atmospheric convection, so there might be a subnormal mode that decreases heat, convection, and evaporation. For example, I can imagine that ocean currents carrying more warm surface waters north or south from the equatorial regions might, in consequence, cool the Equator somewhat. That might result in less evaporation, creating lower-than-normal levels of greenhouse gases and thus a global cooling.

To see how ocean circulation might affect greenhouse gases, we must try to account quantitatively for important nonlinearities, ones in which little nudges provoke great responses. The modern world is full of objects and systems that exhibit "bistable" modes, with thresholds for flipping. Light switches abruptly change mode when nudged hard enough. Door latches suddenly give way. A gentle pull on a trigger may be ineffective, but there comes a pressure that will suddenly fire the gun. Thermostats tend to activate heating or cooling mechanisms abruptly -- also an example of a system that pushes back.

We must be careful not to think of an abrupt cooling in response to global warming as just another self-regulatory device, a control system for cooling things down when it gets too hot. The scale of the response will be far beyond the bounds of regulation -- more like when excess warming triggers fire extinguishers in the ceiling, ruining the contents of the room while cooling them down.

Preventing Climate Flips

THOUGH combating global warming is obviously on the agenda for preventing a cold flip, we could easily be blindsided by stability problems if we allow global warming per se to remain the main focus of our climate-change efforts. To stabilize our flip-flopping climate we'll need to identify all the important feedbacks that control climate and ocean currents -- evaporation, the reflection of sunlight back into space, and so on -- and then estimate their relative strengths and interactions in computer models.

Feedbacks are what determine thresholds, where one mode flips into another. Near a threshold one can sometimes observe abortive responses, rather like the act of stepping back onto a curb several times before finally running across a busy street. Abortive responses and rapid chattering between modes are common problems in nonlinear systems with not quite enough oomph -- the reason that old fluorescent lights flicker. To keep a bistable system firmly in one state or the other, it should be kept away from the transition threshold.

We need to make sure that no business-as-usual climate variation, such as an El Niño or the North Atlantic Oscillation, can push our climate onto the slippery slope and into an abrupt cooling. Of particular importance are combinations of climate variations -- this winter, for example, we are experiencing both an El Niño and a North Atlantic Oscillation -- because such combinations can add up to much more than the sum of their parts.

We are near the end of a warm period in any event; ice ages return even without human influences on climate. The last warm period abruptly terminated 13,000 years after the abrupt warming that initiated it, and we've already gone 15,000 years from a similar starting point. But we may be able to do something to delay an abrupt cooling.

Do something? This tends to stagger the imagination, immediately conjuring up visions of terraforming on a science-fiction scale -- and so we shake our heads and say, "Better to fight global warming by consuming less," and so forth.

Surprisingly, it may prove possible to prevent flip-flops in the climate -- even by means of low-tech schemes. Keeping the present climate from falling back into the low state will in any case be a lot easier than trying to reverse such a change after it has occurred. Were fjord floods causing flushing to fail, because the downwelling sites were fairly close to the fjords, it is obvious that we could solve the problem. All we would need to do is open a channel through the ice dam with explosives before dangerous levels of water built up.

Timing could be everything, given the delayed effects from inch-per-second circulation patterns, but that, too, potentially has a low-tech solution: build dams across the major fjord systems and hold back the meltwater at critical times. Or divert eastern-Greenland meltwater to the less sensitive north and west coasts.

Fortunately, big parallel computers have proved useful for both global climate modeling and detailed modeling of ocean circulation. They even show the flips. Computer models might not yet be able to predict what will happen if we tamper with downwelling sites, but this problem doesn't seem insoluble. We need more well-trained people, bigger computers, more coring of the ocean floor and silted-up lakes, more ships to drag instrument packages through the depths, more instrumented buoys to study critical sites in detail, more satellites measuring regional variations in the sea surface, and perhaps some small-scale trial runs of interventions.

It would be especially nice to see another dozen major groups of scientists doing climate simulations, discovering the intervention mistakes as quickly as possible and learning from them. Medieval cathedral builders learned from their design mistakes over the centuries, and their undertakings were a far larger drain on the economic resources and people power of their day than anything yet discussed for stabilizing the climate in the twenty-first century. We may not have centuries to spare, but any economy in which two percent of the population produces all the food, as is the case in the United States today, has lots of resources and many options for reordering priorities.

Three Scenarios

FUTURISTS have learned to bracket the future with alternative scenarios, each of which captures important features that cluster together, each of which is compact enough to be seen as a narrative on a human scale. Three scenarios for the next climatic phase might be called population crash, cheap fix, and muddling through.

The population-crash scenario is surely the most appalling. Plummeting crop yields would cause some powerful countries to try to take over their neighbors or distant lands -- if only because their armies, unpaid and lacking food, would go marauding, both at home and across the borders. The better-organized countries would attempt to use their armies, before they fell apart entirely, to take over countries with significant remaining resources, driving out or starving their inhabitants if not using modern weapons to accomplish the same end: eliminating competitors for the remaining food.

This would be a worldwide problem -- and could lead to a Third World War -- but Europe's vulnerability is particularly easy to analyze. The last abrupt cooling, the Younger Dryas, drastically altered Europe's climate as far east as Ukraine. Present-day Europe has more than 650 million people. It has excellent soils, and largely grows its own food. It could no longer do so if it lost the extra warming from the North Atlantic.

There is another part of the world with the same good soil, within the same latitudinal band, which we can use for a quick comparison. Canada lacks Europe's winter warmth and rainfall, because it has no equivalent of the North Atlantic Current to preheat its eastbound weather systems. Canada's agriculture supports about 28 million people. If Europe had weather like Canada's, it could feed only one out of twenty-three present-day Europeans.

routes. The only reason that two percent of our population can feed the other 98 percent is that we have a well-developed system of transportation and middlemen -- but it is not very robust. The system allows for large urban populations in the best of times, but not in the case of widespread disruptions.

Natural disasters such as hurricanes and earthquakes are less troubling than abrupt coolings for two reasons: they're short (the recovery period starts the next day) and they're local or regional (unaffected citizens can help the overwhelmed). There is, increasingly, international cooperation in response to catastrophe -- but no country is going to be able to rely on a stored agricultural surplus for even a year, and any country will be reluctant to give away part of its surplus.

In an abrupt cooling the problem would get worse for decades, and much of the earth would be affected. A meteor strike that killed most of the population in a month would not be as serious as an abrupt cooling that eventually killed just as many. With the population crash spread out over a decade, there would be ample opportunity for civilization's institutions to be torn apart and for hatreds to build, as armies tried to grab remaining resources simply to feed the people in their own countries. The effects of an abrupt cold last for centuries. They might not be the end of *Homo sapiens* -- written knowledge and elementary education might well endure -- but the world after such a population crash would certainly be full of despotic governments that hated their neighbors because of recent atrocities. Recovery would be very slow.

A slightly exaggerated version of our present know-something-do-nothing state of affairs is know-nothing-do-nothing: a reduction in science as usual, further limiting our chances of discovering a way out. History is full of withdrawals from knowledge-seeking, whether for reasons of fundamentalism, fatalism, or "government lite" economics. This scenario does not require that the shortsighted be in charge, only that they have enough influence to put the relevant science agencies on starvation budgets and to send recommendations back for yet another commission report due five years hence.

A cheap-fix scenario, such as building or bombing a dam, presumes that we know enough to prevent trouble, or to nip a developing problem in the bud. But just as vaccines and antibiotics presume much knowledge about diseases, their climatic equivalents presume much knowledge about oceans, atmospheres, and past climates. Suppose we had reports that winter salt flushing was confined to certain areas, that abrupt shifts in the past were associated with localized flushing failures, *and*that one computer model after another suggested a solution that was likely to work even under a wide range of weather extremes. A quick fix, such as bombing an ice dam, might then be possible. Although I don't consider this scenario to be the most likely one, it is possible that solutions could turn out to be cheap and easy, and that another abrupt cooling isn't inevitable. Fatalism, in other words, might well be foolish.

A muddle-through scenario assumes that we would mobilize our scientific and technological resources well in advance of any abrupt cooling problem, but that the solution wouldn't be simple. Instead we would try one thing after another, creating a patchwork of solutions that might hold for another few decades, allowing the search for a better stabilizing mechanism to continue.

We might, for example, anchor bargeloads of evaporation-enhancing surfactants (used in the southwest corner of the Dead Sea to speed potash production) upwind from critical downwelling sites, letting winds spread them over the ocean surface all winter, just to ensure later flushing. We might create a rain shadow, seeding clouds so that they dropped their unsalted water well upwind of a given year's critical flushing sites -- a strategy that might be particularly important in view of the increased rainfall expected from global warming. We might undertake to regulate the Mediterranean's salty outflow, which is also thought to disrupt the North Atlantic Current.

Perhaps computer simulations will tell us that the only robust solutions are those that re-create the ocean currents of three million years ago, before the Isthmus of Panama closed off the express route for excess-salt disposal. Thus we might dig a wide sea-level Panama Canal in stages, carefully managing the changeover.

Staying in the "Comfort Zone"

STABILIZING our flip-flopping climate is not a simple matter. We need heat in the right places, such as the Greenland Sea, and not in others right next door, such as Greenland itself. Man-made global warming is likely to achieve exactly the opposite -- warming Greenland and cooling the Greenland Sea.

A remarkable amount of specious reasoning is often encountered when we contemplate reducing carbon-dioxide emissions. That increased quantities of greenhouse gases will lead to global warming is as solid a scientific prediction as can be found, but other things influence climate too, and some people try to escape confronting the consequences of our pumping more and more greenhouse gases into the atmosphere by supposing that something will come along miraculously to counteract them. Volcanos spew sulfates, as do our own smokestacks, and these reflect some sunlight back into space, particularly over the North Atlantic and Europe. But we can't assume that anything like this will counteract our longer-term flurry of carbon-dioxide emissions. Only the most naive gamblers bet against physics, and only the most irresponsible bet with their grandchildren's resources.

To the long list of predicted consequences of global warming -- stronger storms, methane release, habitat changes, ice-sheet melting, rising seas, stronger El Niños, killer heat waves -- we must now add an abrupt, catastrophic cooling. Whereas the familiar consequences of global warming will force expensive but gradual adjustments, the abrupt cooling promoted by man-made warming looks like a particularly efficient means of committing mass suicide.

We cannot avoid trouble by merely cutting down on our present warming trend, though that's an excellent place to start. Paleoclimatic records reveal that any notion we may once have had that the climate will remain the same unless pollution changes it is wishful thinking. Judging from the duration of the last warm period, we are probably near the end of the current one. Our goal must be to stabilize the climate in its favorable mode and ensure that enough equatorial heat continues to flow into the waters around Greenland and Norway. A stabilized climate must have a wide "comfort zone," and be able to survive the El Niños of the short term. We can design for that in computer models of climate, just as architects design earthquake-resistant skyscrapers. Implementing it might cost no more, in relative terms, than building a medieval cathedral. But we may not have centuries for acquiring wisdom, and it would be wise to compress our learning into the years immediately ahead. We have to discover what has made the climate of the past 8,000 years relatively stable, and then figure out how to prop it up.

> Those who will not reason
> Perish in the act:
> Those who will not act
> Perish for that reason.
>
> -- W. H. Auden

The online version of this article appears in two parts. Click here to go to part one.

William H. Calvin is a theoretical neurophysiologist at the University of Washington at Seattle. For more information on Calvin and his writings, see his personal Web site.

Illustrations by Guy Billout

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