Abrupt Climate Changes: Oceans, Ice, and Us

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Synopsis

History supports modern climate science in showing that rising carbon dioxide and other changes from human activities will cause large climate changes that challenge humans. Climate history shows further that unexpected, large, abrupt climate changes are possible, even though they have not been widely included when considering the problems facing us. My impressions of our students, and my fuzzy recollections of human history, suggest that we can meet these challenges and emerge better than ever, but that it will take good support of a lot of our best students to do so.

Introduction: A Challenge

How should we handle our climate future? A government official trying to decide what if anything to do about climate change can choose from many possible futures, with bigger or smaller, scarier or friendlier changes. But almost all those futures are projected to arrive smoothly and gradually, allowing the government and the governed time to respond.

A historian of climate, reading the tale of centuries or of billions of years, will not tell you the future but will assure you that it won't arrive smoothly. Variability is the rule, not the exception. Even if you know which future is coming, you can be sure that it will arrive in fits and starts, and that there may be large and rapid jumps and detours on the way.

Climatologists have studied variability for a long time, of course, but the widespread realization that the variability includes very large and widespread abrupt climate changes is only a decade or so old. Many of the abrupt climate changes of the past have acted on the atmosphere through the ocean, with ice and vegetation playing important roles.

Here, we'll look at a little of the evidence for abrupt climate changes, discuss what probably caused them, and then ask whether they have anything to tell us about the future (the answer is "Yes"). Then I'll offer a few opinions about the future, based on the good climate science and my impressions of modern students and recent environmental history.

Mired in Mud

The plants and animals living in cold places differ from their warm-weather cousins. Planktonic shells that accumulate on the sea floor beneath the Gulf Stream are readily distinguished from those of colder waters, and the pollen accumulating on a tundra lake bed has little in common with that in a temperate or tropical forest. Because sediment piles preserve shells and pollen in order, younger on top of older, anyone with the resources and patience can read a history of climate from the indicators in a sediment core.

Centuries ago, investigators had already noticed evidence of climate changes. Some of these changes reached deep into time, with sea shells in rocks on mountain peaks and ferns pressed between sedimentary layers from the frozen depths of Antarctica. Other changes were much more recent, preserved in muds not yet turned to stone. Records of warmings and coolings, wettings and dryings were found. And surprisingly, the remains of different climates were often very close together in the muds, suggesting sudden shifts in conditions.

Of particular interest to our story, European bogs showed that the warming from the ice age had staggered back to cold conditions more than once, with one reversal especially prominent. Named for evidence of a pretty little tundra flower, *Dryas octopetala*, in places now too warm for it, the most recent major cold interval was called the Younger Dryas, to distinguish from older occurrences of evidence of the plant in sediments. The Younger Dryas had involved regrowth of glaciers and other changes, and seemed to have started and ended abruptly. (1)

But how abruptly? How much cooling had occurred? How much of the world had been affected? The discoverers of the Younger Dryas lacked the technology to find out. But increasingly, we are learning that the changes were very large, rapid, and widespread, affecting much or all of the world in a decade or so to as little as a single year, with changes locally at least as large as 10^{o}C or 18^{o}F.

Into the Ice

Ocean, lake and bog floors are good places to study past climate changes, but there are difficulties. In most lakes and oceans, sediment accumulates very slowly, and sometimes burrowing worms stir the mud a little, so that you can't tell exactly how rapidly things occurred. To learn even more, and in greater detail, probably the best place to go is to ice in Antarctica, and high mountains, and for this story, especially the ice of Greenland. (2)

Snow falls on the ice sheet, and is gradually squeezed into a pile of ice that now is hundreds of kilometers or miles across and three kilometers (two miles) thick in the middle. The ice spreads slowly under its own weight like pancake batter on a griddle, dripping off the edges of the island to form icebergs or melting in low-elevation coastal regions. The rate of ice loss is not too different from the rate of snowfall over the last millennia, so the total volume of the ice sheet hasn't been changing greatly over that time.

Snow that falls traps bits of dust, sea salt, forest-fire smoke, volcanic ash, odd isotopes made by cosmic rays in the atmosphere, and more. As the snow is squeezed to ice, trapped bubbles preserve a record of the composition of the air itself, including "swamp-gas" methane, nitrous oxide from various bacteria mostly in wet places around the world, and more. Summer sunshine changes the physical properties of the snow, so summer and winter are marked in the ice like the rings of a tree. Subtle isotopic indicators in the ice and the trapped gases reveal the temperature in Greenland when the snow fell, as does the actual temperature of the ice today—the ice is coldest 1-2 km down (about a mile) because it has not finished warming from the ice age. By reading the records in a Greenland ice core—temperature and snowfall in Greenland, wind-blown dust from Asia (fingerprinted by its unique chemical composition and minerals), methane from the world's wetlands—one can learn much about the climate in Greenland and something about the climate in many places far from Greenland. And because changes in the sun or in the Earth's magnetic field affect the cosmic rays that make odd isotopes in the ice, and volcanic ash block sunshine before falling on the ice sheet, one can learn something about the causes of climate changes as well.

Many deep ice cores have been collected from Greenland and analyzed over the last 40 years, including the early Camp Century and Dye 3 cores, the coastal Renland core, and the deep cores at GISP2 (Figure 1), GRIP and NGRIP. I was fortunate to participate in the GISP2 project between 1989 and 1993, near the center of the ice sheet.

The results from the many Greenland cores are consistent and spectacular, and agree closely with the older studies from other locations. Greenland cooled over tens of thousands of years into the great ice age that peaked about 20,000 years ago, along with the rest of the world, as slow changes in Earth's orbit and resulting changes in atmospheric greenhouse gases combined to spread vast ice sheets across North America and Eurasia. The return of sunshine to the north, and the drop in greenhouse gases, then warmed Greenland above recent temperatures a few thousand years ago, and brought it to the present (Figures 2, 3).

Riding on the back of these large but slow changes are the abrupt climate changes that have caught so much attention. Numerous times, Greenland's temperature jumped many degrees (as much as 16^{o}C or 28^{o}F) in decades to as little as years (Figures 4, 5). These jumps were accompanied by order-of-magnitude changes in dustiness, and shifts in methane approaching twofold. When Greenland was cold and dry, more dust and less methane arrived in Greenland, indicating generally cold, dry and windy conditions across much of the globe. Greenland's snowfall seems to have doubled in a single year at the end of the Younger Dryas. Abrupt, indeed.

Of course, while we were working in Greenland, colleagues were still coring into the ocean muds and lake sediments, into trees and cave formations, and developing wonderful new records that confirmed and extended the ice-core data. When Greenland was cold, weaker monsoons allowed large areas of Asia (Figure 6) and Africa to dry, the tropical weather patterns shifted south in the Americas to dry some areas and wet others, and changes spread around the world. (3) Importantly, the northern cold brought warmth to the far south, providing an important clue to what happened.

Explaining the Excesses

This crazy behavior took many climate scientists completely by surprise. Day differs greatly from night, and summer from winter, because of huge changes in the amount of sunshine. Over tens of thousands of years, Earth's orbital features change sunshine at particular latitudes by more than 10% to pace ice ages, although mostly by moving sunshine to other latitudes on the planet rather than by changing the total sunshine received, with the global response of the ice ages caused by changes in carbon dioxide and other greenhouse gases. And over millions of years or longer, the sun changes, continents move, mountains grow and are eroded to steer wind and water, all changing climate. (4)

But year to year, the sun is nearly the same, the orbits are barely changed, the continents and their mountains remain almost unmoved. How could the climate suddenly jump? To answer this question, we must consider oceans and ice.

We know that the oceans affect climate, in many ways. Kansas swings intriguingly from winter blizzard to summer heat, while climatic ennui grips San Franciscans as the nearby ocean moderates near-coastal conditions. Carolinians enjoy warmer swimming than their California relatives because warmer currents hug the west sides of northern oceans while colder currents bathe the east sides.

The difference between the surface temperatures on east and west sides of oceans arises largely from wind-driven currents, which move much of the water and heat carried by the oceans in huge, shallow gyres. But riding along with the wind-driven currents off the Carolinas as part of the Gulf Stream is water with a very different fate. This water will split off to the north, cool in the wintertime, sink into the cold abyss, and begin an odyssey that takes it south through the depths of the Atlantic, around the raceway of the Southern Ocean off Antarctica, and north into the deep Pacific or Indian Oceans. Eventually, mixing driven by winds or tides will help bring the water to the surface, back around into the South Atlantic, and northward across the equator to the Gulf Stream.

This thousand-year loop goes by various names, including the thermohaline circulation, the overturning circulation, and the great oceanic conveyor. The overturning of this conveyor belt moves more water than all the world's rivers, and helps moderate the climate of northwestern Europe and beyond by bringing water warmed by South Atlantic sunshine to moderate northern winters. The name "thermohaline" comes from the fact that only very dense water can sink to the depths, and colder and saltier waters are denser. The surface water is saltier in the Atlantic than in the Pacific because the trade winds blow steadily across the narrow neck of Central America, supplying rain to the Pacific that evaporated from the Atlantic. This Atlantic evaporation leaves salt behind, and the conveyor is the ocean's way of taking the salt to the Pacific to rejoin the fresh rainwater.

But, looking at a map shows that the North Atlantic is a rather small basin, not nearly so broad as the Pacific. In fact, many of us with interests in the North Atlantic remember a pointed riddle asked by oceanographers interested in bigger waters: "What do you call the study of the North Atlantic? Limnology!" This linkage to lakes was considered to be a real thigh-slapper.

Surprisingly, this smallness may contribute to the importance of the basin. One can contemplate delivery of enough fresh water to dilute the North Atlantic's surface salinity to match that of the North Pacific. Once diluted, even if cooled to the freezing point, the North Atlantic surface waters would float on denser waters from the Antarctic.

Whether polar ocean water sinks before it freezes, or freezes before it sinks, is a powerful switch. A winter near the North Atlantic today is not extremely pleasant, with fog and wind and drizzle. But freeze the surface, and temperatures could plunge tens of degrees, shifting London and Oslo toward Moscow's frigid winters. (5)

And this has happened in the past, many times. About 8200 years ago, near the peak natural warmth after the last ice age, a great flood happened. The ice sheet on Canada had been melting back into Hudson Bay, but still plugged the outlet of the bay. The world's largest lake was backed up by the ice, looking for a way out. When an ice dam fails, it does so quickly—heat from turbulence in water melts ice, enlarging channels—so ice-dam failures have produced the largest floods known on Earth. So, the dam eventually failed, and the lake was dumped into the North Atlantic, probably within a single year. For the decades after, cold spread from North America across Greenland into Europe and perhaps completely around the Earth, the tropical rains shifted south away from the coast of Venezuela, lakes dried in Africa, and other climatic changes happened. (6)

Further back in time, when the North American ice sheets were still rather large, a similar ice-dammed lake burst out from near Lake Superior, triggering the Younger Dryas. Following that flood, the ocean became "stuck" in the cold, fresh, pattern with extensive wintertime sea ice for more than a thousand years before the conveyor restarted. And still further back, other floods and surges of ice sheets are tied to freshening of the North Atlantic and additional abrupt climate changes. The longer-lived events show up in climate records from Antarctica and off the coast of Chile, but as warm times, not cold. When the conveyor slows or stops because of North Atlantic freshening, sunshine-warmed South Atlantic waters remain in the South Atlantic rather than flowing to the north, and may even flow south to become really cold and sink around Antarctica, so the south and north play on a temperature see-saw.

Freshness in the North Atlantic has never succeeded in staying, however. The trade winds blow across Central America whether the North Atlantic is cold and fresh or warm and salty. If the conveyor is turned off, the continuing trade-wind flow will raise the salinity of the whole Atlantic even as fresh waters continue to pool on the North Atlantic surface. Eventually, the Atlantic will become salty enough to turn the conveyor back on somehow, and the extra salt needed to do this will cause the flow to be especially vigorous at the start. A huge, abrupt northern warming will follow.

So What?

The evidence is really remarkably clear. Big, fast changes happened repeatedly in the past across much of the Earth. Among the many things that happened, the plants and animals living across most of the Earth were forced to move, often huge distances. Living in the same way in the same places didn't work after the abrupt climate changes. The lesson should be clear; if such a change were to happen today, we would be impacted, too, in large ways. We can't just pick up and move, because there are people living where we'd want to go. And other living things can't move easily, either, because our farms and highways are in the way.

Fortunately for us, the huge ice-marginal lakes that triggered many of the past coolings are long gone, so we don't face exactly the same problems as before. Nonetheless, we cannot easily dismiss the record of the past, for several reasons, including that human activities might change the North Atlantic, and that there are many other "switches" in the climate system beyond the North Atlantic that humans or nature might flip.

The key to North Atlantic changes has been the supply of freshwater; if too much, the waters freeze before they sink, causing cold, dry and windy conditions to spread. Humans are now conducting a great "experiment" with the climate, rapidly pumping carbon dioxide and other greenhouse gases into the atmosphere. Each week, a typical American driver spends $20 or so to put nearly 100 pounds of gasoline into a car, and then turns that gasoline into about 300 pounds of CO2 that go into the atmosphere. Compared to our trash, this waste stream is very large, but we don't see it or smell it like trash. The CO2 traps heat to warm the planet, as surely as a blanket spread over you warms your sleep at night. Just as with blankets, some CO2 in the atmosphere is good, but too much can cause problems. As we turn 500 million years of nature's accumulation of coal, oil and natural gas into 500 years of easy energy and CO2 emissions, we are exceeding the planet's ability to quickly soak up the CO2, which is accumulating in the atmosphere. (7)

Two of the many likely effects of this rising CO2 will be to increase high-latitude precipitation and ice melt. More precipitation around the Arctic Ocean and the North Atlantic will increase freshwater supply to the North Atlantic. More melting of Arctic glaciers and permafrost, and the huge ice sheet on Greenland, will have the same effect. Could this extra freshwater change the conveyor circulation? Possibly. Most of the big, complex computerized climate models used to project future changes indicate a slowdown in the ocean circulation, but not a complete collapse, and the slowdown takes long enough that CO2 replaces the warmth from the ocean circulation. The most common outcome is that warming occurs in the North Atlantic, but more slowly than elsewhere in and near the Arctic. However, there is a tendency for these big models, when tested against the results of the past, to change less or more slowly than the real world did. And simpler models, when run into the future, sometimes produce larger changes including local cooling around the North Atlantic while the rest of the world warms. When one complex model was recently forced hard enough to simulate a complete shutdown of the North Atlantic circulation, widespread drying also occurred, with strong shifts in precipitation patterns much like those of the past, and with a simulated reduction in total plant growth on Earth. And, while we don't know that the threshold for North Atlantic shutdown is being approached, we do know that the expected speed-up in supply of fresh water from precipitation and ice melt is occurring, with oceanic changes that seem to have surprised oceanographers. (8)

So there is a possibility that human activities could shift North Atlantic circulation, with large impacts on ecosystems and economies. A change as big and scary as those recorded in the ice cores is not likely, but something almost that big may not be entirely impossible. Monitoring efforts are underway, but we're not very close to being able to make accurate predictions yet.

Could there be other surprises out there in the climate system, thresholds that, if crossed, will rapidly switch us into a new and very different pattern? Again, the answer appears to be "yes". Consider briefly two of the possibilities: collapse of an ice sheet, and onset of persistent droughts. Both have happened in the past, both could happen in the future, and both are linked to the oceans again.

The ice sheets are perhaps the easiest to understand. At the end of the last ice age, about 30% of our modern land area was under ice sheets, and sea level was nearly 400 feet lower than today. Beyond the ice, the ocean had retreated far from our modern coasts, and many islands and continents were connected by land bridges. Then, as sunshine rose in the north from orbital changes, and as CO_2 rose from resulting shifts in the chemistry of the oceans, much of that ice melted. Sea level rose rapidly, averaging about 1 cm (close to half an inch) per year for nearly 10,000 years, and going much faster than that at times, flooding about 20% of the exposed land area as ice was removed from a similar area.

Today, about 10% of the land is under thick ice sheets, which hold enough water to raise sea level more than 70 m (more than 200 feet). That ice includes about 0.5 m (a foot or two) of sea level locked in mountain glaciers, about 7 m (more than 20 feet) in the Greenland Ice Sheet, nearly as much in the West Antarctic ice sheet, and the rest across the Transantarctic Mountains in the largest, coldest ice sheet in East Antarctica. The mountain glaciers have been melting as the world has warmed over the last century (Figure 7), and together with expansion of the ocean waters as they have warmed, has contributed to the sea-level rise of about 2 mm/year (nearly an inch per decade) over the last century. That sea-level rise, though far slower than the peak rates during the last ice age, has contributed to the retreat of beaches on the U.S. east coast that has forced rescue efforts for historical lighthouses, to increasing flooding in Venice and Bangladesh, and to the growing problems of keeping the ocean out of New Orleans the next time a hurricane strikes. (7)

As recently as a few years ago, it appeared that the great ice caps were not contributing to that sea-level rise, but recent research shows an acceleration of mass loss from important coastal regions of Greenland and West Antarctica. In Greenland, some of the change seems to have come from increased melting of low-elevation, near-coastal ice, and perhaps from a speed-up of ice flow as this meltwater drained through holes in the glacier to the bed and lubricated the ice so it could more easily skate over the rock beneath. And both in Greenland and Antarctica, some of the speed-up has been tied to oceanic attack of the ice-sheet margins. (9)

Flow from a big ice sheet usually doesn't make icebergs just where the ice begins to float. Instead, the ice remains attached to the ice sheet and flows out over the ocean to make an ice shelf, with icebergs breaking off the end of the ice shelf. In many places, these ice shelves exist in embayments, and the moving ice must shove past slower-moving ice before making bergs; in other places, the ice shelves run aground on islands in the ocean before reaching the calving front. The sides and islands help slow the ice flow, pushing back on the non-floating ice. But ocean water circulates under ice shelves. Warm the water, and the ice shelf will melt from below. As the ice thins, it may lose contact with islands and weaken at the sides, reducing the push back and allowing the ice sheet to spread and make icebergs more rapidly. The new research shows that over the last decade, this has happened to the small ice shelf that helped restrain Jakobshavn ice stream in Greenland, allowing speed-up of what was already the ice-sheet region with the fastest sustained flow of any on Earth. The same seems to have happened to several glaciers that drain vast regions of the West Antarctic ice sheet into Pine Island Bay, causing thinning and speed-up that have penetrated far into the ice sheet, and flotation of marginal regions. Along the Antarctic Peninsula, the melting from below was joined by surface meltwater that wedged open crevasses in part of the Larsen ice shelf, which then fell apart over just a very few days or weeks, freeing ice behind to flow more rapidly.

The total contribution of these to sea-level rise is not large. But if warming continues and accelerates in the future, larger changes may be possible. In West Antarctica, very much larger ice shelves closer to the pole are now apparently stable, but could be attacked in a warmer world, freeing much more ice to contribute to sea-level rise. And in Greenland, if the ice spreads and thins enough, the cold upper reaches will move down into warmer regions where melting is possible. A threshold may be crossed beyond which the ice sheet cannot maintain itself. The time for losing an ice sheet such as Greenland or West Antarctica is probably millennia but might possibly be only centuries. Looking at the populations, the land area, the value of the land that would be vulnerable to loss of Greenland or West Antarctica (all of Florida south of the Everglades, for example), loss of even part of one of the big ice sheets would be a large event (Figure 8). And the most important control may be the rate at which oceans deliver heat beneath the ice shelves. Notice the interesting dilemma in Greenland—rapid melting might be self-limiting because the fresh water could slow the conveyor circulation, but with the possible large impacts of conveyor changes.

Perhaps the most interesting issue for humans is slightly less global, and one which I know less about. Humans have long experienced droughts, which seem rarely to have been good for us. Collaborations between paleoclimatologists and archaeologists are increasingly uncovering links between drought and declines in important groups of people, including the ancestral Puebloans of Mesa Verde and surroundings in the southwestern US, the classical Maya, and the Akkadian empire. We haven't been watching the weather with modern instruments long enough to know just how big and long droughts might be, but tree-ring and other records indicate mega-droughts in many regions that have lasted decades or centuries. The Dust Bowl of the U.S. Great Plains during the 1930s appears as a short, small event in some drought records, compared to much longer and larger events centuries or millennia earlier. (10)

Some aspects of droughts are easy to understand. Random variability can cause a drought in a region that on average gets just enough rainfall. By speeding evaporation, warmer temperatures shorten the time from the last rainfall to the onset of plant wilting and drought; this contributes to the result of many climate models that drought will become more common and severe in grain-belt regions in a warmer future, even though rainfall is likely to increase globally. Much of the rainfall in some regions such as the U.S. Great Plains is water that has just evaporated from plants, and which was pulled out of the soil by the plant roots. If plants wilt, they are no longer preventing that water from soaking through the soil into rocks and then into streams; hence, wilting from a lack of rainfall reduces rainfall further.

An important observation is that the oscillations in the Pacific Ocean associated with the El Nino phenomenon are important causes of droughts. The changes in sea-surface temperatures steer rain and storms. In a La Nina state, warm waters in the western equatorial Pacific give drenching rains in Indonesia and parts of Australia, while cold waters off Peru suppress evaporation and storm formation, bringing dry conditions. But let the trade winds slacken, the warm waters spread east, and South American rain is joined by Indonesian and Australian drought. Furthermore, circulation patterns change southward to the Antarctic and northward into the U.S., shifting patterns and bringing droughts to some and floods to others. (11)

Over the last centuries, El Ninos have come and gone, without getting stuck in one mode for more than months or a very few years. Paleoclimatic records indicate that the size and persistence of El Ninos have changed over longer times, and vigorous research is now directed to learning what is possible and likely in the future.

In addition to El Nino, more subtle patterns of persistent sea-surface-temperature anomalies have been observed. Some might be linked somehow to El Nino, but the patterns are not understood especially well. Recently, researchers have used measured patterns of sea-surface temperatures to force models of the atmosphere. The striking result is that the history of the Dust Bowl is simulated rather accurately, and seems to arise from subtle, degree-or-less anomalies in the Pacific temperatures, and the African Sahelian drought of the last decades is similarly explainable from the sea-surface-temperature anomalies in nearby oceans (with a little help perhaps from human pollution affecting weather patterns). (12)

Now What?

So what is one to make of all of this? We know that humans are affected by climate. We're clever enough to live almost everywhere, so climate doesn't control us, but it surely matters. The climate has always changed, and always will. But we humans are pushing the climate rapidly in unexpected directions, cutting forests, damming rivers, paving landscapes, burning fossil fuels, and more. The result is highly likely to be a warmer world on average, with sea-level rise and many other changes, only some of which are easy to project with much confidence. How much warmer probably depends more on us than on nature, and on whether we get serious about finding alternatives to burning fossil fuels, releasing the CO2, and leaving it in the Earth system. Such alternatives could include conservation of energy, switching to non-carbon-producing energy sources, and capture of carbon dioxide where it is produced or from the air followed by sequestration away from the atmosphere. (13)

Looking at the past, we find that carbon dioxide and warmth have gone together (Figure 2, for example), and that the carbon dioxide provides the best explanation of the correlation, improving confidence in the future projections. But we also find that strange things have happened—huge and abrupt shifts in climate over much of the world, ice-sheet collapses speeding sea-level rise, persistent droughts, and more. Many of these have causes, but often those causes seem to have brought the Earth system to some threshold, after which the climate did more or less what it wanted, faster than the cause and often going in a surprising direction. As we face a future of great change, it is worth remembering well this strangeness of the past, and the possibility that we might join nature in triggering strangeness in the future that could challenge us. It also seems prudent to include the possibility of such strangeness, of abrupt climate change, in assessing what if anything should be done about climate change.

The remarkably intertwined nature of the Earth system is illustrated clearly by the abrupt climate changes of the past. Even a simple discussion of climate change quickly raises numerous questions about everything from ocean mixing to plant roots. As a specialist in ice, the important role played by ice in causing, amplifying, and recording the past changes gives me confidence that much remains for students of ice to solve, and I'm happy to encourage students on such a path. I also am struck with how important the oceans have been in this story; putting a fresh-water and sea-ice cap on the North Atlantic has repeatedly dried out the Asian monsoon, and even subtle changes in Pacific temperature seem capable of contributing to massive social disruption thousands of miles away.

I remain optimistic about the environmental challenges from climate change. We humans have faced a great range of previous challenges, from the ozone hole and phosphate pollution of Lake Erie, all the way back to human waste before sewers. In those environmental problems that I've lived through, a good idea (new refrigerants, for example, or better detergents) had unexpected consequences (ozone destruction, or over-fertilization greatly changing lake ecosystems). As I remember it, a vigorous and often acrimonious public debate followed in which science only occasionally played the leading role. Those who advocated cleaning up the problem were usually opposed by arguments that: i) there really isn't a problem; and ii) if there is a problem, nature is doing it, not humans; and besides, iii) it would be too expensive to clean up the problem, anyway. Soon after, however, a new, improved idea appeared (low-phosphate detergents, or ozone-friendlier refrigerants), the problem was greatly reduced or eliminated at rather low cost, new industries or products were established that gave people employment and contributed to the economy, and we are left to wonder how we got along before. DDT attacking raptor egg shells, acid rain, and lead from gasoline are other such environmental issues that were improved greatly with much less pain and agony than predicted by some. I even have the nagging suspicion that the solutions often came from industries that, until they had the solutions in hand, were busily arguing that solutions were neither possible nor necessary.

We really can't conceive of going back to dumping chamber pots out windows on passers-by below, but real investments were required to get indoor plumbing, sewers, and sewage-treatment plants, and these remain scarce in some parts of the world. Nor are we likely to go back to previous high levels of lead, DDT, phosphate, acid rain, or chlorofluorocarbons.

Similarly, I am optimistic that our great-great-great grandchildren will control atmospheric carbon dioxide at levels to best suit themselves. Professionals in new industries will make good livings doing so. This is not a scientific judgement based on detailed study, of course; it is the opinion of one scientist who was fortunate enough to be given the lectern for an exciting hour.

But to get to this future, we will need the genius of humanity, to understand energy options and engineering well enough to solve the challenges, and to understand the climate system well enough to know what we want and how to get there. These are among the great challenges facing humanity, and they will be met better if our students are better supported in their endeavors.

Notes and references

(1) Weart, S. 2003. The discovery of rapid climate change. Physics Today 56(8), 30-36.

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(3) Key papers include Hughen, K.A., J.T. Overpeck, S.J. Lehman, M. Kashgarian, J. Southon, L.C. Peterson, R. Alley and D.M. Sigman, 1998, Deglacial changes in ocean circulation from an extended radiocarbon calibration, Nature 391, 65-68, and Wang, Y.J., H. Cheng, R.L. Edwards, Z.S. An, J.Y. Wu, C.C. Shen and J.A. Dorale, 2001, A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China, Science 294(5550), 2345-2348.

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Figure Captions

Figure 1. Ice cores, such as these from GISP2 in central Greenland, produce wonderful records of climate change.

Figure 2. Last 440,000 years of climate in central East Antarctica, from the Vostok ice core (Petit et al., 1999). Today is on the left, and 440,000 years ago on the right. The lower curve shows the history of temperature estimated from the isotopic composition of the ice. The large, approximately 100,000-year cycle of ice ages is evident. This basic pattern is also evident in most climate records from anywhere on Earth. The bottom curve also shows the variation in local sunshine in Antarctica over the more recent part of the record, calculated from knowledge of orbital physics. A record from the north shows high sunshine when the south is low for the most part, because of the effect of the orbits moving sunshine around on the planet (it is a bit more complicated than this, but not greatly). The coldest time of the most recent ice age occurs when the south was getting a peak in sunshine, but the north was in a valley. The only explanation of this behavior that “works” is that the carbon-dioxide concentration of the atmosphere followed northern sunshine, as shown by the upper curve, and that in turn carbon dioxide was more important for southern temperature than was southern sunshine. Figures 2-5 are modified from The Two-Mile Time Machine, which lists sources, etc. (14)

Figure 3. As in Figure 2, but the curves have been compressed to show the likely future trend in carbon dioxide if humans do not change our behavior. Nature indeed has changed atmospheric greenhouse gases greatly in the past, but humans are now “in control” and moving out of the natural range of variability for at least the last 440,000 years.

Figure 4. History of snowfall (bottom) and temperature (top), somewhat smoothed, for central Greenland from the GISP2 core. Large and surprising changes have occurred, including the Younger Dryas event, indicated.

Figure 5. A longer view of the history of temperature in Greenland, showing the numerous large and abrupt changes (to 16^oC or 28^oF) riding on the back of the ice-age cycle.

Figure 6. Cave-formation history of water availability in China (Wang et al., in ref. 3), and of temperature in Greenland, showing that cold in Greenland has occurred with dry in China.

Figure 7. Small glacier beyond the main ice sheet, Stauning Alps, east Greenland. During the ice age, everything shown was under ice. Readvance of the glacier during the Younger Dryas produced prominent sediment piles (moraines) outlining the glacier's extent, including those seen prominently in the lower left of the photograph. At the end of the Little Ice Age about 100 years ago, the glacier occupied the light-colored region. Today, the glacier is much reduced, and is barely visible in the upper left of the photograph. Water from the melt-back since the Little Ice Age has contributed to sea-level rise.

Figure 8. Graphic illustration of what might happen if Greenland Ice Sheet (GIS), West Antarctic Ice Sheet (WAIS), and East Antarctic Ice Sheet (EAIS) were to melt, courtesy of Byron Parizek. This is not a prediction, but it is interesting.

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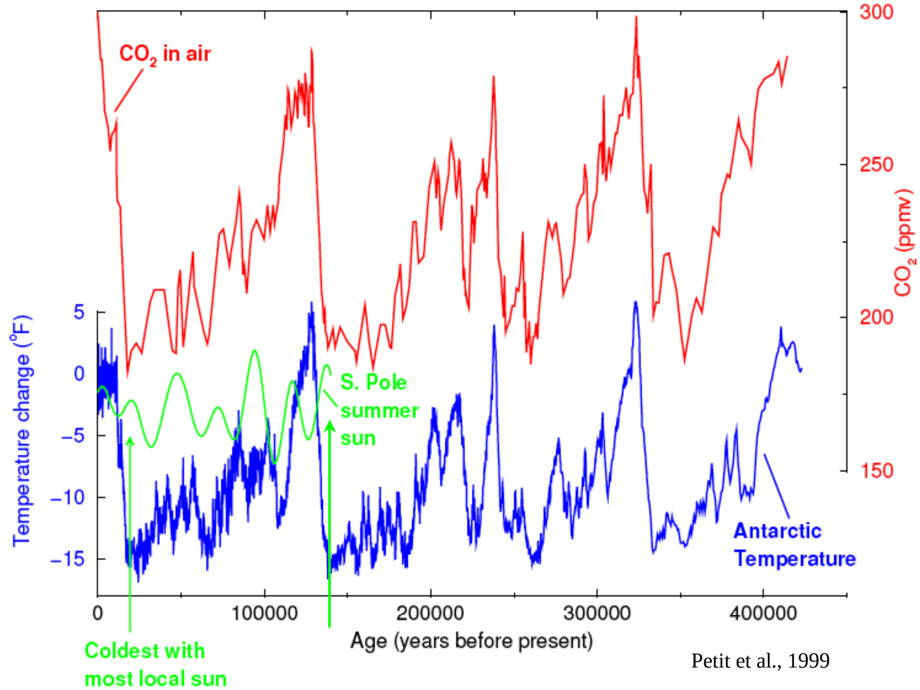

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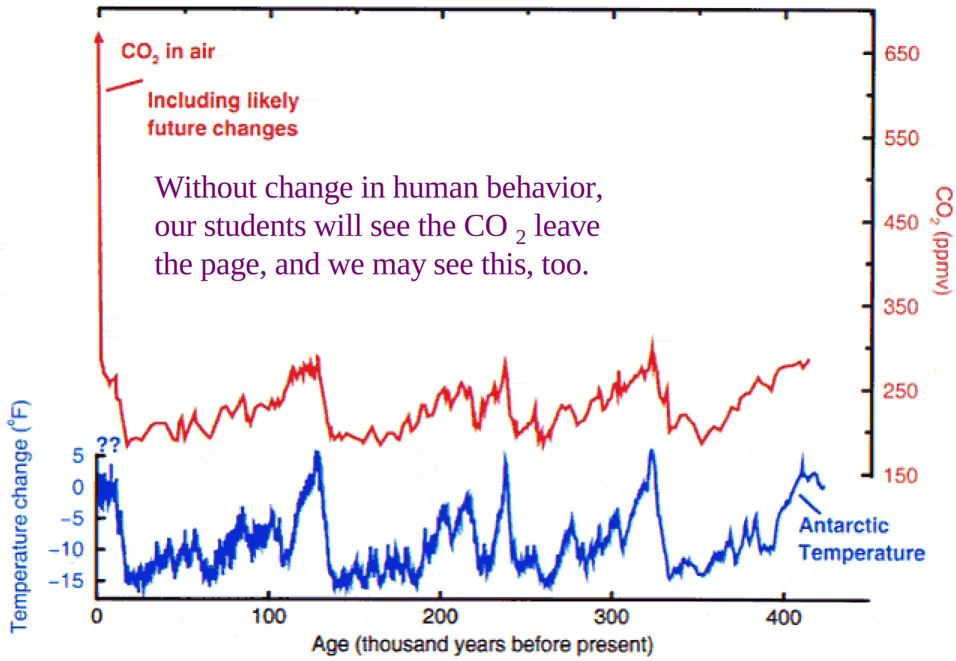

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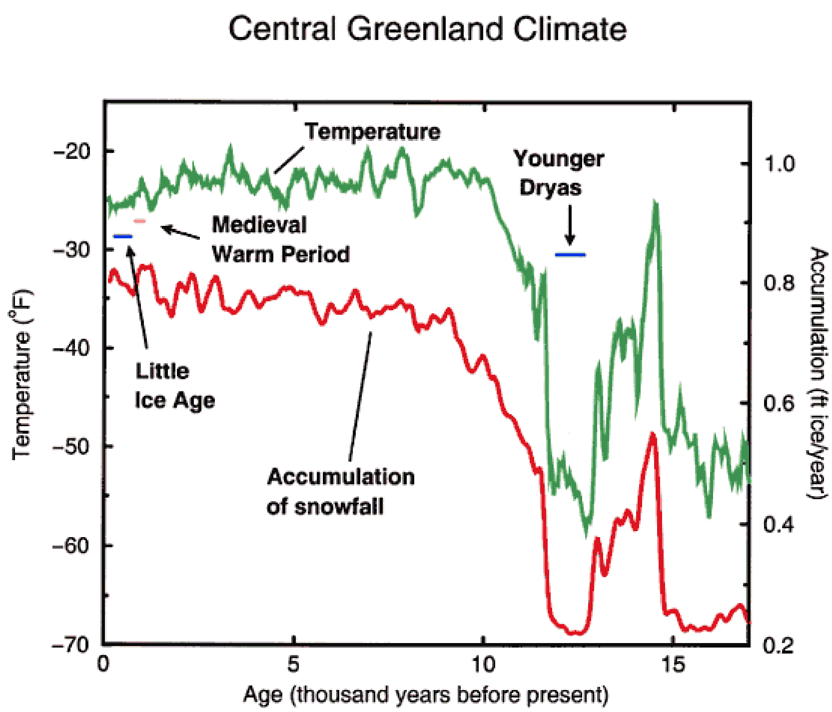

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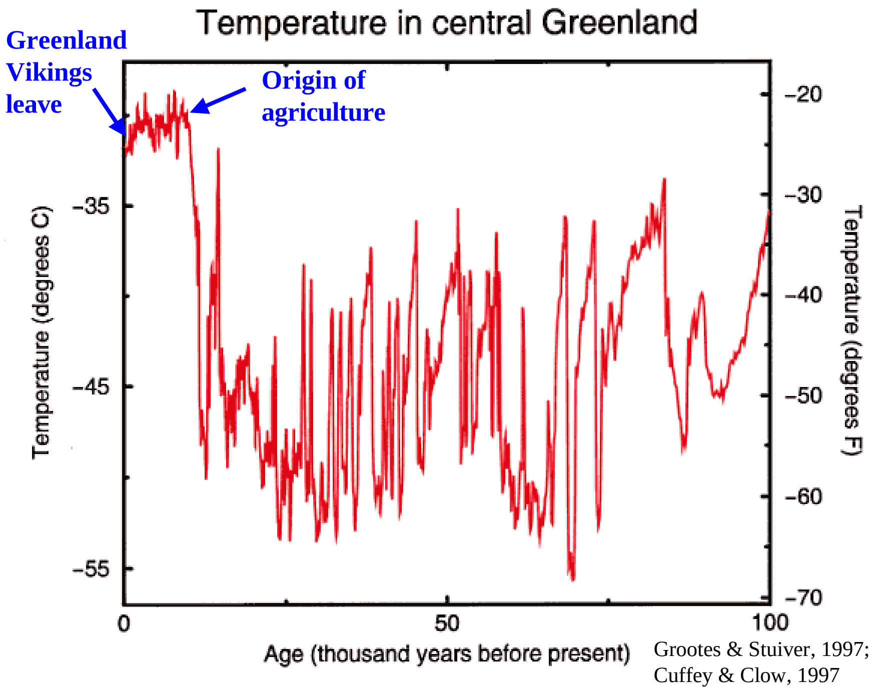

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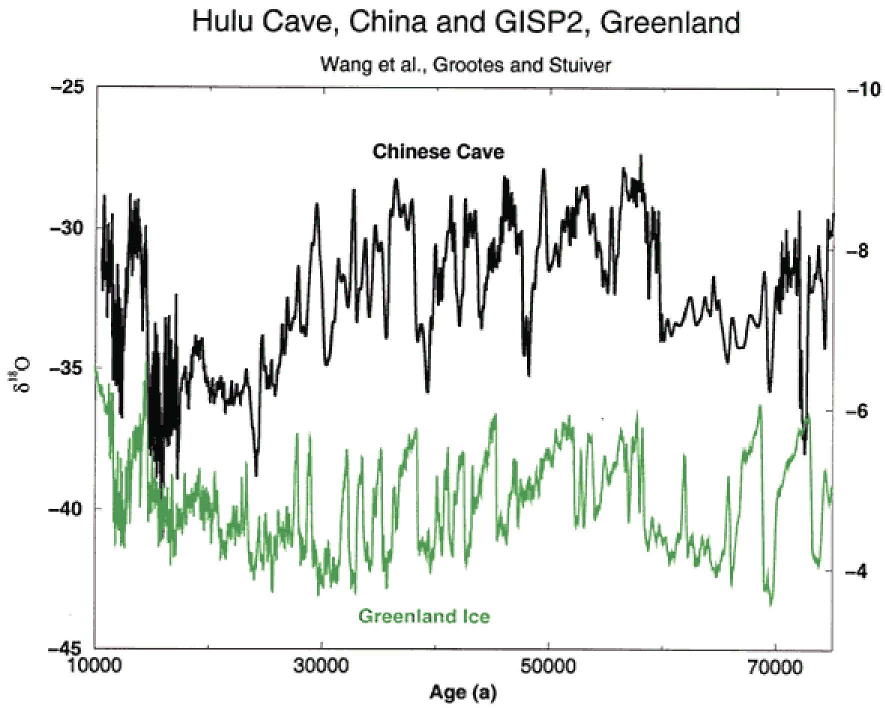

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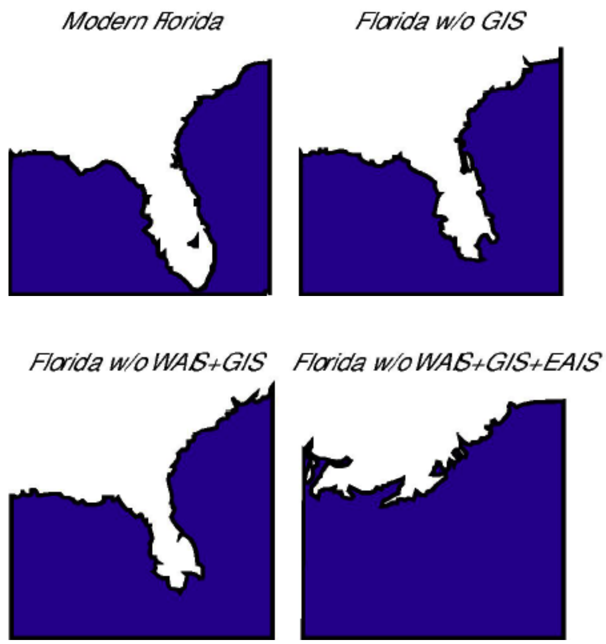

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