Abrupt Climate Changes: Oceans, Ice, and Us

BY RICHARD B. ALLEY

Presenting the Sixth Annual Roger Revelle Commemorative Lecture given November 10, 2004 at the Baird Auditorium at the Smithsonian Museum of Natural History in Washington, D.C. This lecture series was created in 1999 by the National Research Council's Ocean Studies Board in honor of the late Dr. Roger Revelle, a leader in the field of Oceanography for almost a half a century, in order to highlight the important links between ocean sciences and public policy.

SYNOPSIS

Modern climate science indicates that rising carbon dioxide levels in the atmosphere and other effects of human activities will cause large climate changes requiring significant adaptation by human societies around the globe. Climate records and human history provide insight into the nature of climate change and the types of challenges a shifting environment will pose for humankind. The geologic record shows that climate sometimes changes abruptly, but this aspect of climate history has received relatively little attention in efforts to understand the consequences of future climate change. Although a major, potentially rapid change in climate is a daunting prospect, I am convinced that today's students, if given sufficient training and financial support, will be able to address the climate challenges of the future.

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INTRODUCTION: A CHALLENGE

How should we handle our climate future? In trying to decide what if anything to do about climate change, policy-makers may consider a wide range of future scenarios, with larger or smaller, scarier or more acceptable changes. But almost all those scenarios postulate change that occurs smoothly and gradually, leaving the government and the governed plenty of time to respond.

This view of climate is surprising because Earth's climate history is anything but smooth. Variability is the rule, not the exception. However, only in the past decade or so has the broader scientific community recognized that variability includes very large and widespread abrupt climate changes. The relatively recent revelations gleaned from the climate record tell us that change will occur in fits and starts, with potentially large and rapid jumps and detours along the way.

After presenting some of the evidence for abrupt climate changes and describing the likely causes, I will discuss whether the past has anything to tell us about the future (the answer is yes).

Then I will offer a few opinions about the future based on the science of climate, my impressions of recent environmental history, and the potential of this generation of students.

MIRED IN MUD

Earth's history is recorded in sediments. Because plants and animals that grow in warm environments can be readily distinguished from those that grow in cold environments, variation in the plant and animal skeletons found in sediment layers indicates that there were shifts in the climate at that location. For instance, skeletons of planktonic microorganisms that accumulate on the seafloor beneath the warm waters of the Gulf Stream are readily distinguished from those of nearby cooler waters. Similarly, pollen that accumulates on a tundra lake bed has little in common with pollen from a temperate or tropical forest. Sediment cores have revealed alternating accumulations of layers of cold- and warm-water organisms. Sometimes these layers occur close together, suggesting sudden shifts in conditions.

Of particular interest, European bogs showed that warming since the ice age staggered back to cold conditions several times, with one especially prominent reversal. This most recent major cold interval (about 12,800 years ago) was called the Younger Dryas after a tundra flower (*Dryas octopetala*) that appears in the mud record from that time, but disappears when European conditions become temperate. Conditions characteristic of cold periods, such as the regrowth of glaciers, appear to have started and ended abruptly during the Younger Dryas[1].

But how abruptly? How much cooling occurred? How much of the world was affected? The discoverers of the Younger Dryas lacked the technology to find out, but now we are learning that the changes were rapid and dramatic, with local temperatures changing as much as 10°C (18°F) or more over a decade or so. Additionally, the climate shift moved quickly, spreading around much of the globe within about a decade, possibly as quickly as a single year.

INTO THE ICE

Although sediments of ocean, lake, and bog floors have provided important evidence of past climate changes, it is difficult to resolve how rapidly events occurred because sediments often accumulated very slowly. Burrowing animals literally can stir up the past, thus, disrupting parts of the record. Ice provides higher resolution and better preservation of past events, inspiring scientists to seek ice cores from Antarctica, high mountains, and, for my story, the ice sheet of Greenland[2] (Figure 1).

Figure 1. Ice cores, such as this one from Greenland Ice Sheet Project 2 (GISP2) in central Greenland, produce wonderful records of climate change. The ice cores pictured here are being studied by Mark Meier (left) and the author (right) at the National Science Foundation-U.S. Geological Survey's U.S. National Ice Core Laboratory, located in Denver, Colorado.

Snow that falls on an ice sheet is gradually squeezed into ice, which piles up over time. The ice in Greenland is now hundreds of kilometers across and three kilometers (about 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 Greenland to form icebergs or melting in low-elevation coastal regions. The rate of ice loss has been close to the rate of snowfall, keeping the volume of the ice sheet relatively constant over the last millennia.

Summer sunshine changes the physical properties of snow, providing a seasonal marker in the ice like the rings of a tree. As snow falls, it traps bits of dust, sea salt, smoke from forest fires, volcanic ash, and other materials from the atmosphere. Bubbles get trapped when the snow is squeezed into ice, thus capturing a time capsule of air that can be analyzed for gases that fluctuate with climate, such as methane and nitrous oxide. Measurements of subtle isotopic indicators and trapped gases have been used to de-

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

[2] Much has been written about Greenland ice cores, spanning at least hundreds and perhaps thousands of scientific papers now. I am biased in favor of the popular account in Alley, R.B., 2000, *The Two-Mile Time Machine*, Princeton University Press, New Jersey. For a more detailed starting point to the literature, see Hammer, C., P.A. Mayewski, D. Peel, and M. Stuiver, 1997, Preface to Greenland Summit Ice Cores, *Journal of Geophysical Research* 102(C12), 26,315-26,316, and all other papers in the same issue (approximately 47 papers) from pages 26,315 to 26,886. The paper by Severinghaus, J.P., T. Sowers, E.J. Brook, R.B. Alley, and M.L. Bender, 1998, Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice, *Nature* 391(6663), 141-146 is especially relevant in showing how widespread and abrupt the climate changes were. Abrupt climate change in general is treated in National Research Council, 2002, *Abrupt Climate Change: Inevitable Surprises*, National Academies Press, Washington, D.C.

termine the temperature in Greenland when the snow fell. The actual temperature of the ice today also provides evidence of past cooling—the ice is coldest 1 to 2 km down (about a mile) because of the lingering chill 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 other parts of the world. Also, because changes in the sun or in Earth's magnetic field affect the cosmic rays that make some of the odd isotopes found in the ice, and volcanic ash blocks sunshine before falling on the ice sheet, ice cores provide some information on the causes of climate changes.

Several deep ice cores have been collected from Greenland and analyzed over the past 40 years. I was fortunate to participate in GISP2 (Greenland Ice Sheet Project 2) between 1989 and 1993, near the center of the ice sheet.

Results from the many Greenland ice cores are spectacular and agree closely with previous studies from other locations. The cores tell us that Greenland cooled with the rest of the world (over tens of thousands of years) into the great ice age that peaked about 20,000 years ago. The ice ages were paced by slow changes in Earth's orbit. Remarkably, the orbital changes had little effect on the total energy received from the sun, serving instead to move sunshine around on the planet. Cooling occurred worldwide when sunshine dropped in the far north, because northern sunshine affected atmospheric carbon-dioxide concentrations and thus global temperatures—Antarctica experienced especially cold temperatures when its sunshine was especially high, as shown in Figure 2[3]. When sunshine shifted from the south to the north, carbon dioxide rose in the atmosphere, Greenland warmed with the rest of the world, and has remained warm to the present (Figures 2 and 3). (Many other hypotheses have been suggested for ice ages, but so far have failed. The only plausible explanation of what happened requires that global average temperature increases with increasing carbon-dioxide concentration in the atmosphere. And as shown in Figure 3, future changes in carbon dioxide concentration are likely to be large compared to those involved in the global ice ages.)

Riding on the back of these slow, large changes are the abrupt climate changes that have caught so much recent attention. Numerous times, Greenland's temperature jumped many degrees (as much as 16°C or 28°F) in decades or even just a few years (Figures 4 and 5). These jumps were accompanied by order-of-magnitude changes in dustiness and almost two-fold shifts in atmospheric methane. When Greenland was cold and dry, more dust and less methane reached 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.

While we were working in Greenland, colleagues were still coring into 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, the monsoons were weaker, causing large areas of Asia (Figure 6) and Africa to dry out. Tropical weather patterns shifted south in the Americas, changing precipitation[4]. Importantly, the cold north brought warmth to the far south—providing an essential clue to what had 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, features of Earth's orbit change sunshine at particular lati-

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[3] For some insight to controls on atmospheric carbon-dioxide concentrations over ice-age cycles, see, W.S. Broecker, and T.-H. Peng, 1998, *Greenhouse Puzzles*, 2nd ed., Eldigio Press, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York. One partial explanation of how reduced northern sunshine led to lower carbon-dioxide concentrations and global cooling, involves the ability of dust to fertilize the ocean, growing more plants that remove carbon dioxide from the atmosphere. Most land, hence most dust, is in the northern hemisphere, and the cooling and drying associated with reduced northern sunshine increase dust delivery to the ocean. For additional insights on ice-age cycles, see Alley, R.B., 2000, *The Two-Mile Time Machine*, Princeton University Press, New Jersey; or Imbrie, J., and K.P. Imbrie, 1979, *Ice Ages: Solving the Mystery*, Enslow Publishers, Hillside, New Jersey (now a little dated, but still insightful), and introductory texts, such as Bradley, R.S., 1999, *Paleoclimatology*, Academic Press, San Diego, California; and Cronin, T.M., 1999, *Principles of Paleoclimatology*, Columbia University Press, Palisades, New York.

[4] 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.

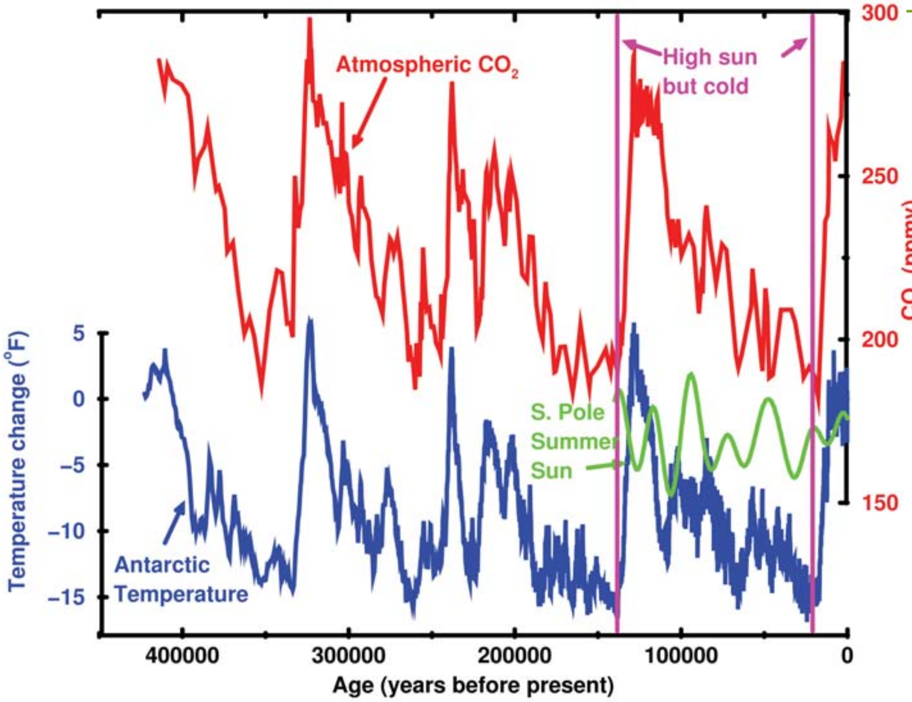

Figure 2. The last 440,000 years of climate in central East Antarctica, from the Vostok ice core. Today is on the right, and 440,000 years ago on the left. The lower curve shows the history of temperature estimated from the isotopic composition of the ice. The large, approximately 100,000-year cycle of ice ages is evident. This basic pattern is also evident in most climate records obtained from anywhere on Earth. Also shown is the variation in local sunshine in Antarctica over the best-dated and more recent part of the record, calculated from knowledge of orbital physics. Peaks in Antarctic sunshine are spaced about 20,000 years apart, and occur when northern sunshine was especially low, including the Antarctic peak in sunshine about 20,000 years ago when Antarctica was especially cold. 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.

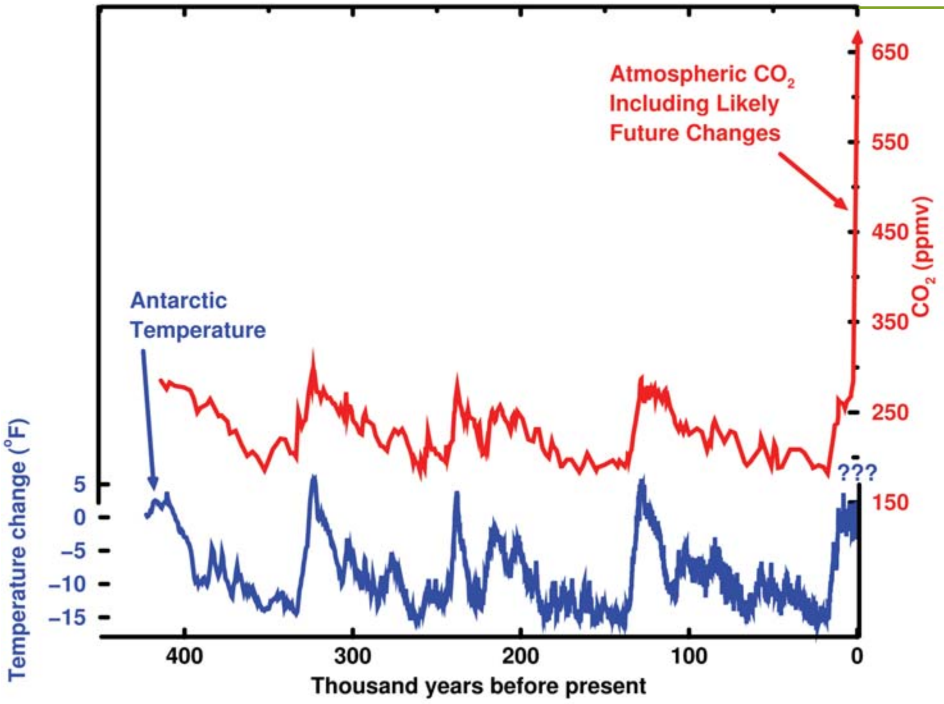

Figure 3. Similar to Figure 2, but the curves have been compressed to show the likely future trend in carbon dioxide if we do not change our behavior. Nature indeed has changed atmospheric greenhouse gases greatly in the past, but humans are now "in control" and moving out of the natural range of variability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

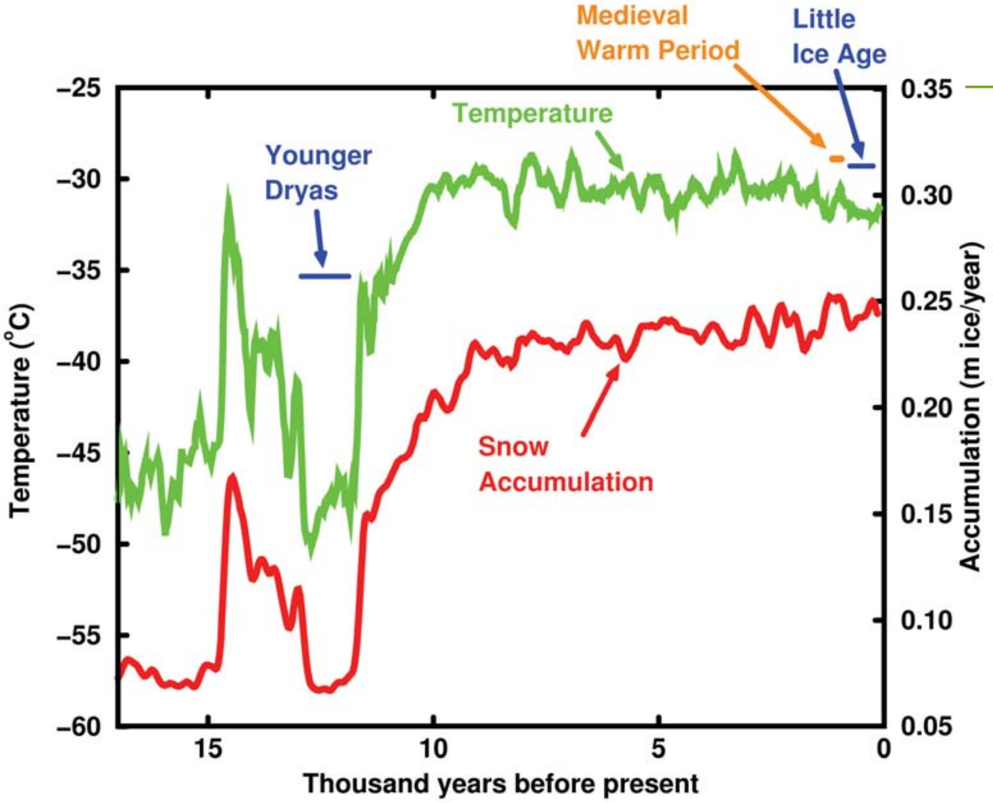

Figure 4. History of snowfall (bottom) and temperature (top), somewhat smoothed, for central Greenland from the GISP2 core. Large and surprising changes have occurred, including the Younger Dryas event (indicated in this figure).

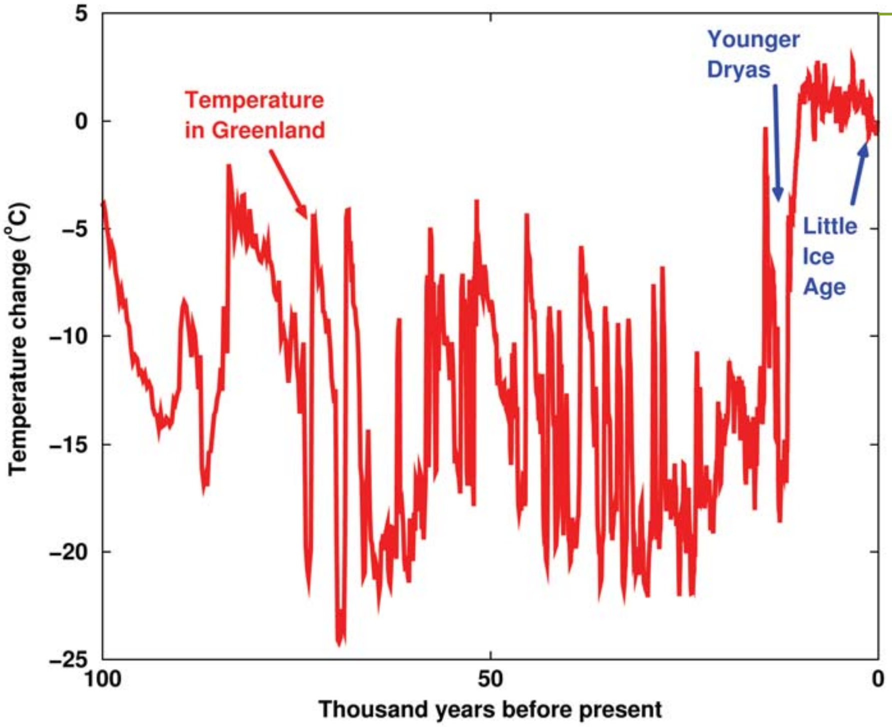

Figure 5. A longer view of the history of temperature in Greenland, showing the numerous large and abrupt changes (to 16°C or 28°F) riding on the back of the ice-age cycle.

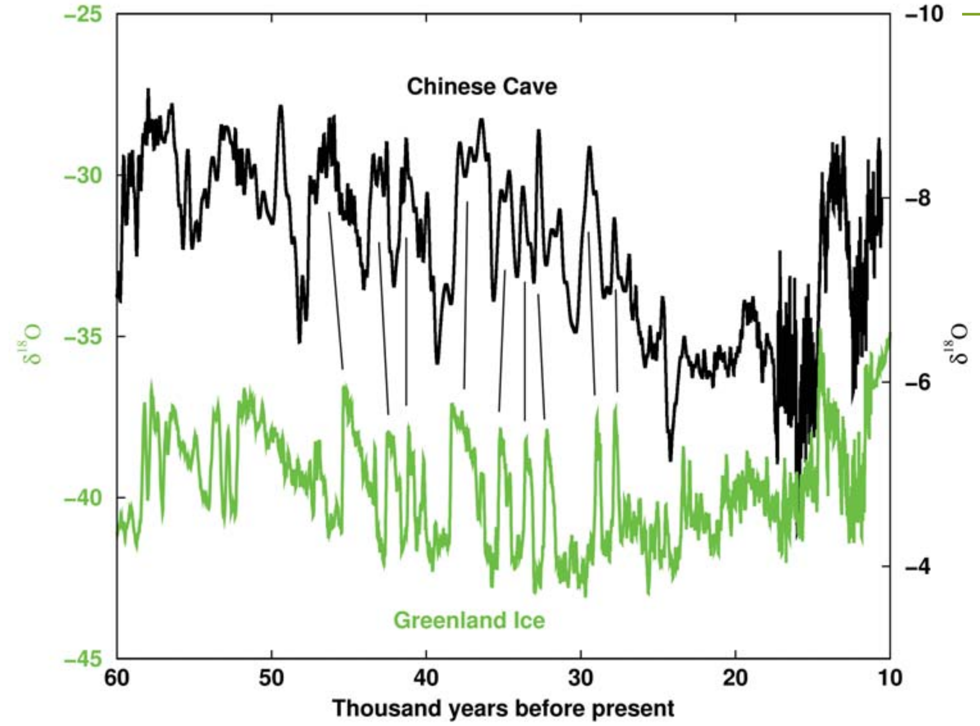

Figure 6. Cave-formation record of water availability in China and of temperature in Greenland, showing that cold in Greenland has occurred with dryness in China. Small lines have been added to show likely correlative events; dating is independent and not perfect for the two records. The isotopic ratio of ice (left) is primarily an indicator of temperature, with warmer conditions plotting higher, and the isotopic ratio of the cave formation (right) is primarily an indicator of rainfall amount, with wetter conditions plotting higher.

tudes by more than 10 percent to pace ice ages, although mostly by moving sunshine to other latitudes rather than by changing the planet's total sunshine (with the global response of ice ages caused by changes in carbon dioxide and other greenhouse gases). And over millions of years or longer, the sun changes, continents move, and mountains grow and are eroded to steer wind and water, all changing climate.

But year to year, the sun is nearly the same, the orbits are barely changed, the continents and their mountains are not notably altered. 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 conditions. Carolinians enjoy warmer swimming than their California relatives because warmer currents from the south bathe the eastern edges of northern continents while colder currents from the north hug the western 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. However, water with a very different fate rides along with the wind-driven currents of the Gulf Stream off the Carolinas. 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 by transferring heat from South Atlantic sunshine to the northern latitudes. The term "thermohaline circulation" refers to the density-driven movement of water around the world's ocean basins, with density determined by the water's salinity and temperature. When high-salinity water cools, the increase in density causes the water to sink to the depths. Surface water is saltier in the Atlantic than in the Pacific because the trade winds evaporate water from the Atlantic, blow across the narrow neck of Central America, and freshen Pacific waters through rain. The conveyor is the ocean's way of taking the extra salt left in the Atlantic to rejoin the fresh rainwater in the Pacific.

The North Atlantic is a rather small basin, not nearly as broad as the Pacific. Some oceanographers interested in larger waters used to twit those of us who cared about the North Atlantic with the riddle: "What do you call the study of the North Atlantic? Limnology!" This linkage to lakes was considered to be a real thigh-slapper. But the dynamic properties of the North Atlantic basin are a function of its small size. Extra freshwater input to the North Atlantic can reduce its surface salinity to match that of the North Pacific. Even if cooled to the freezing point, these diluted North Atlantic surface waters would float, not sink.

In terms of climate, it matters whether the polar ocean water sinks before it freezes, or freezes before it sinks. Winter around the North Atlantic is cool and wet, with fog and wind. But if the surface waters froze, temperatures could plunge tens of degrees, bringing winters more like those of Moscow to London and Oslo[5].

Europe has felt the chill from this phenomenon many times in the past. For example, about 8200 years ago, near the peak natural warmth after the last ice age, a great flood occurred. The ice sheet on Canada had been melting back but still filled Hudson Bay, damming northward flow of meltwater to create the world's largest lake. When an ice dam fails, it fails quickly. Heat from turbulence in water melts ice and enlarges channels, producing the largest floods known on Earth. The Hudson Bay dam eventually failed, dumping a massive load of freshwater into the North Atlantic, probably within a single year. For decades afterward, cold spread from North America across Greenland into Europe and perhaps completely around the globe, the tropical rains shifted south away from the coast of Venezuela, and lakes dried in Africa, among other climatic changes[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 were 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 periods, 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. Cooling and sinking of water may increase around Antarctica. Hence, balmy weather in the high latitudes goes with the flow, seesawing between north and south.

Freshness in the North Atlantic has never persisted, however. The trade winds blow across Central America whether the North Atlantic is cold and fresh or warm and salty. Hence, even when the conveyor stops, the trade winds evaporate water and increase the salinity of the entire Atlantic, eventually raising the salinity of the North Atlantic surface waters enough to restart the conveyor. The Atlantic becomes extra salty before reaching this turning point, activating an especially vigorous flow at the beginning. An abrupt, dramatic warming of the northern latitudes marks the resumption of the conveyor.

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[5] The great oceanic conveyor, its changes, interruptions, and its see-saw behavior have especially been brought to widespread attention by W.S. Broecker, in papers including Broecker, W.S., M. Andree, W. Wolfli, H. Oeschger, G. Bonani, J. Kennett and D. Peteet, 1988, The chronology of the last deglaciation: Implications to the cause of the Younger Dryas event, *Paleoceanography* 3, 1-19; Broecker, W.S., and G.H. Denton, 1989, The role of ocean-atmosphere reorganization in glacial cycles, *Geochimica et Cosmochimica Acta* 53, 2465-2501; Broecker, W.S., G. Bond, and M. Klas, 1990, A salt oscillator in the glacial Atlantic? 1: The concept, *Paleoceanography* 5, 469-477; Broecker, W.S., 1997, Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance? *Science* 278(5343), 1582-1588; and Broecker, W.S., 1998, Paleocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography* 13(2), 119-121.

[6] For the 8 ka event, see Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor, and P.U. Clark, 1997, Holocene climatic instability: A prominent, widespread event 8200 years ago, *Geology* 25(6), 483-486; Barber, D.C., A. Dyke, C. Hillaire-Marcel, A.E. Jennings, J.T. Andrews, M.W. Kerwin, G. Bioldeau, R. McNeely, J. Southon, M.D. Morehead, and J.M. Gagnon, 1999, Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature* 400(6742), 344-348; Clarke, G.K.C., D.W. Leverington, J.T. Teller, and A.S. Dyke, 2004, Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event, *Quaternary Science Reviews* 23(304), 389-407.

SO WHAT?

The evidence is really remarkably clear. Large, abrupt changes across much of Earth happened repeatedly in the past. Among the many consequences, plants and animals were forced to move, often great distances. After an abrupt climate change, life did not continue as usual. The lesson should be obvious—if such a change were to happen today, even our modern society would be affected. However, we cannot simply pick up and move because people already live where we would want to go. And other living things can't move easily, either, because our farms and highways are in the way.

The huge ice-marginal lakes that triggered many past cool periods are long gone. Nonetheless, we cannot easily dismiss the record of the past because human activities and natural processes could potentially affect the North Atlantic and many other "switches" in the climate system.

The North Atlantic switch has been flipped by the supply of freshwater; if there is too much freshwater, the waters freeze before they sink, causing cold, dry, and windy conditions to prevail in the region. Human society is now conducting a vast experiment with the climate by rapidly pumping carbon dioxide and other greenhouse gases into the atmosphere. Each week, a typical American driver spends $30 or so to put nearly 100 pounds of gasoline into a car, and then turns that gasoline into about 300 pounds of carbon dioxide released into the atmosphere. Compared to solid trash, this waste is huge, but we don't see it or smell it. Carbon dioxide traps heat and warms the planet, just as a blanket traps the warmth of your body in bed. By turning the 500-million-year accumulation of carbon in coal, oil, and natural gas into 500 years of easy energy and carbon dioxide emissions, we are exceeding the planet's capacity to soak up carbon dioxide. The result will be a high-carbon dioxide atmosphere[7].

Rising carbon dioxide will likely bring increased precipitation and melting ice to high latitudes, increasing the freshwater supply to the North Atlantic. Could this extra freshwater change the conveyor circulation? Possibly. Most complex climate models project a slowdown in ocean circulation, without a complete collapse. The slowdown would occur over decades or longer. Most model outcomes suggest that warming would occur in the North Atlantic; however, it would occur more slowly than elsewhere in and near the Arctic, with higher levels of carbon dioxide replacing the heat lost as warm ocean currents slow. However, when these models are tested for their ability to replicate past climate changes, they show much skill but tend to underestimate the size or rate of change. When simpler models are used to project future climate, they sometimes produce greater change that includes local cooling around the North Atlantic as the rest of the world becomes warmer. One complex model was programmed recently to simulate a complete shutdown of North Atlantic circulation. The results included widespread drying, with strong shifts in precipitation patterns much like those of the past, and projected reduction in total plant growth on Earth. Although we do not know if the threshold for shutdown of North Atlantic circulation is being approached, we do know that the expected speed-up in freshwater supply from precipitation and ice melt is occurring, with changes in ocean conditions that have surprised oceanographers[8].

Hence, there is a possibility that our activities could shift the North Atlantic circulation and cause large impacts on ecosystems and economies. Most likely, the change will not be as large as past events identified in ice cores, but a change almost as large is not unthinkable. Accurate predictions are not yet possible, but monitoring efforts are underway to detect early indicators of change.

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 possibili-

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[7] Authoritative sources on human effects and climate change include: Intergovernmental Panel on Climate Change, 2001, *Third Assessment Report: Climate Change 2001*, A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, R.T. Watson, and the Core Writing Team, eds., Cambridge University Press, United Kingdom, available online at http://www.ipcc.ch; and the report of the National Research Council, 2001, *Climate Change Science: An Analysis of Some Key Questions*, National Academies Press, Washington, D.C.

[8] The IPCC includes assessment of the future of ocean circulation. Also see Stocker, T.F., and A. Schmittner, 1997, The influence of CO_2 emission rates on the stability of the thermohaline circulation, *Nature* 388(6645), 862-865; and Rahmstorf, S., and A. Ganopolski, 1999, Long-term global warming scenarios computed with an efficient coupled climate model, *Climatic Change* 43(2), 353-367. Observed changes in the North Atlantic include Curry, R., B. Dickson, and I. Yashayaev, 2003, A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature* 426(6968), 826-829. For recent simulations of the effect of extra freshwater on the North Atlantic, see Wood, R.A., M. Vellinga, and R. Thorpe, 2003, Global warming and thermohaline circulation stability, *Philosophical Transactions of the Royal Society of London* 361A, 1961-1974.

ties: 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 again to the oceans.

The ice sheets are perhaps the easiest to understand. At the end of the last ice age, about 30 percent of the current land area was under ice sheets, and sea level was more than 100 m (nearly 400 feet) lower than today. The ocean had retreated far from the modern coastline, and many islands and continents were connected by land bridges. Then, with a change in Earth's orbit, sunshine rose in the north and atmospheric carbon dioxide increased (from changing oceanic chemistry and perhaps biology), causing much of the ice to melt. Sea level rose rapidly, averaging about 1 cm per year for nearly 10,000 years and rising much faster at times. About as much land was flooded as was exposed when the ice melted.

Today, about 10 percent of the land is under thick ice sheets holding enough water to raise sea level more than 70 m (about 230 ft). About a half meter of sea-level rise is locked in mountain glaciers, about 7 m in the Greenland ice sheet, nearly as much in the West Antarctic Ice Sheet, and the remainder 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 the thermal expansion of the ocean, this has contributed to a sea-level rise of about 2 mm/yr (nearly an inch per decade) over the last century. That rate of sea-level rise, though far slower than the peak rates during the last ice age, has contributed to the loss of beaches on the east coast of the United States, to flooding in Venice, Italy, and the nation of Bangladesh, and to the growing problem of how to keep the ocean out of New Orleans the next time a hurricane strikes[7].

Just a few years ago, it appeared that the great ice caps were not contributing to sea-level rise, but more-recent research shows an acceleration of ice loss from important coastal regions of Greenland and West Antarctica. In Greenland, some of the change appears to have come from increased melting of low-elevation ice near the coast. Also, the extra meltwater may have accelerated ice flow by draining through holes in the ice to the glacier bed and lubricating the ice so it skates more easily over the rock beneath. Both in Greenland and Antarctica, some of the accelerated ice loss has been attributed to the impact of the ocean on ice-sheet margins[9].

Typically, flow from a big ice sheet will not produce icebergs at the site where the ice begins to float. Instead, ice remains attached to the ice sheet and flows out over the ocean to make an ice shelf, with icebergs breaking off at 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 icebergs. In other places, the ice shelves run aground on islands before reaching the calving front. The flanking land and islands help slow the ice flow, pushing back on the non-floating ice. At the same time, ocean water is circulating under the ice shelves. If this ocean water warms, the ice shelf will melt from below and become thinner. Thinner ice may lose contact with islands and weaken at the sides, allowing the ice sheet to spread and make icebergs more rapidly. New research shows that over the past decade, the small ice shelf that helped restrain Jakobshavn ice stream (a.k.a. Greenland Ice Sheet) in Greenland has thinned, accelerating what was already the fastest sustained flow of any ice-sheet region 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, with thinning and speed-up penetrating far into the ice sheet. Along the Antarctic Peninsula, ice-shelf melting from below was augmented by surface meltwater wedging open crevasses in part of the Larsen ice shelf. The shelf fell apart quickly, over only a few days or weeks, freeing the ice behind it to flow more rapidly.

The total contribution of these events to sea-level rise is not large. But if warming continues and accelerates in the future, larger increases in sea level are possible. In West Antarctica, much larger ice shelves closer to the South Pole ap-

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[9] Important recent papers on ice-sheet changes include Zwally, H.J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen, 2002, Surface melt-induced acceleration of Greenland ice-sheet flow, *Science* 297(5579), 218-222; Thomas, R.H., W. Abdalati, E. Frederick, W.B. Krabill, S. Manizade, and K. Steffen, 2003, Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland, *Journal of Glaciology* 49(165), 231-239; Scambos, T.A., J.A. Bohlander, C.A. Shuman, and P. Skvarca, 2004, Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophysical Research Letters* 31(18), L18402, doi 10.1029/2004GL020670; Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas, 2004, Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, *Geophysical Research Letters* 31(18), L18401, doi 10.1029/2004GL020697; and Thomas, R., E. Rignot, G. Casassa, P. Kanagaratnam, C. Acuna, T. Akins, H. Brecher, E. Frederick, P. Gogineni, W. Krabill, S. Manizade, H. Ramamoorthy, A. Rivera, R. Russell, J. Sonntag, R. Swift, J. Yungel, and J. Zwally, 2004, Accelerated sea-level rise from West Antarctica, *Science* 305(5692), 255-258.

Figure 7. Small glacier beyond the main ice sheet, Stauning Alps, East Greenland. During the ice age, everything shown was under ice. Re-advance of the glacier during the Younger Dryas produced prominent sediment piles (moraines) outlining the glacier's extent, including those seen clearly 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 it is barely visible in the upper left of the photograph. Water from the melt-back since the Little Ice Age has contributed a little to sea-level rise, as have numerous other glaciers melting around the world.

pear stable, but could become vulnerable in a warmer world, releasing much more ice into the ocean. In Greenland, if the ice spreads and thins enough, the cold upper reaches will move down into warmer regions where melting occurs. A threshold may be crossed beyond which the ice sheet cannot maintain itself. Loss of an ice sheet such as Greenland or West Antarctica could occur over millennia, but possibly in as short a time as a few centuries. Considering the populations, land area, and value of coastal land (all of Florida south of the Everglades, for example), loss of even part of one of the big ice sheets of Greenland or West Antarctica would be a major event (Figure 8). The most important factor may be the rate at which ocean currents deliver heat to the waters beneath the ice shelves. Note the interesting dilemma in Greenland—rapid melting could be self-limited if the increased freshwater flow slowed the ocean conveyor, but this could trade sea-level rise for other costly climate changes.

Large, abrupt-onset droughts also might occur if the climate system is pushed across a threshold. Although somewhat less global in impact than a conveyor shutdown or ice-sheet collapse (and further removed from my primary expertise), droughts are of great interest. Droughts have afflicted humans in the past, often causing serious reversals of fortunes. Collaborations between paleoclimatologists and archaeologists have uncovered links between drought and the decline of earlier civilizations including the Ancestral Puebloan (Anasazi) peoples of Mesa Verde and other enclaves in the southwestern United States, the Mayans of Central America, and the Akkadians in the Middle East. Weather has not been monitored with sophisticated instruments long enough to understand the extent and lengths of droughts, but tree rings and other records indicate that mega-droughts in several regions have lasted decades or centuries. The Dust Bowl of the North American Great Plains during the 1930s appears as a short, small event in some drought records, compared to the 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. When the climate warms, evaporation is higher and the time from the last rainfall to the onset of plant wilting and drought is

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[10] For drought, the following workshop report is a good starting point: *A Multi-Millennia Perspective on Drought and Implications for the Future*, report from a CLIVAR/PAGES/IPCC workshop held November 19-21, 2003, in Tucson, Arizona, available online at http://www.ipcc.ch/pub/tucson.pdf; also see Trenberth, K., J. Overpeck, and S. Solomon, 2004, Exploring drought and its implications for the future, *Eos, Transactions, American Geophysical Union* 85 (3), 27; and Laird, K.R., B.F. Cumming, S. Wunsam, J.A. Rusak, R.J. Oblesby, S.C. Fritz, and P.R. Leavitt, 2003, Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia, *Proceedings of the National Academy of Sciences* (USA), 100(5), 2483-2488.

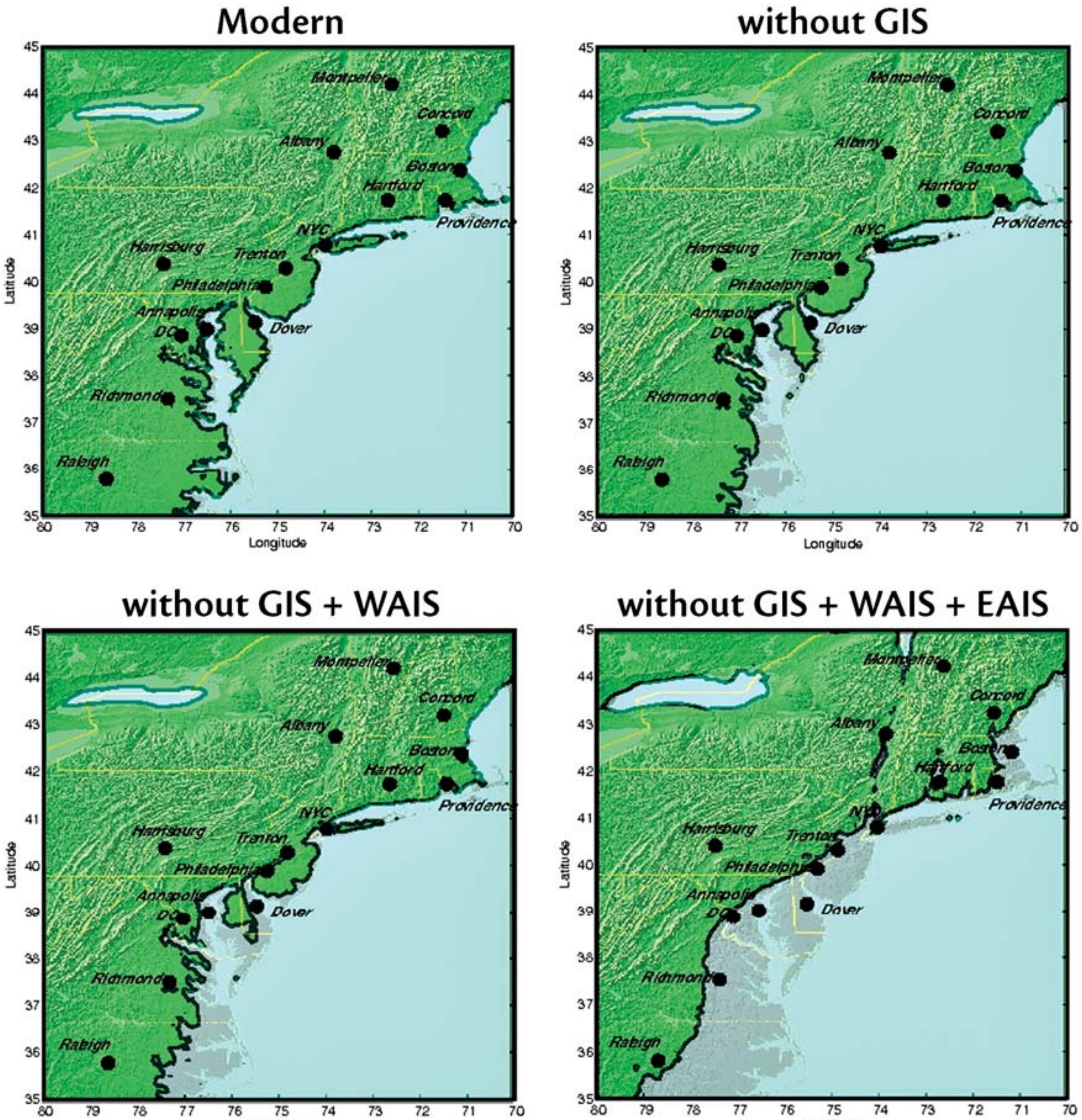

Figure 8. Graphic illustration of what might happen if the Greenland Ice Sheet (GIS), the West Antarctic Ice Sheet (WAIS), and the East Antarctic Ice Sheet (EAIS) were to melt. This is not a prediction, only an interesting conjecture.

shorter. This is observed in many climate models, which project that drought will become more common and severe in grain-growing regions even though rainfall is likely to increase globally. Much of the rainfall in regions such as the Great Plains originates from water evaporated from plants, water that was drawn out of the soil by plant roots. If plants wilt, there will be less evaporation, with water instead seeping through the soil and eventually reaching streams. Hence, when plants wilt due to heat and lack of rain, the reduced evaporation further diminishes rainfall.

An important observation is that the oscillations in the Pacific Ocean associated with the El Niño phenomenon are major causes of droughts. Changes in sea-surface temperatures affect the paths followed by storms. Under La Niña conditions, warm waters amass in the western equatorial Pacific and bring drenching rains to Indonesia and parts of

Australia, while cold waters off Peru suppress evaporation and storm formation, bringing dry conditions. But if the trade winds slacken, the warm waters spread east, and South American rain is joined by Indonesian and Australian drought. Furthermore, circulation patterns shift southward to the Antarctic and northward into the United States, affecting weather patterns and bringing droughts to some regions and floods to others[11].

During past centuries, El Niños have come and gone, without getting stuck in one mode for more than several months or a year or two. Paleoclimatic records indicate that the size and persistence of El Niños have varied over geologic time, and vigorous research is now directed towards learning what is possible and likely in the future.

In addition to El Niño, more subtle patterns of persistent sea-surface-temperature anomalies have been observed. Some might be linked in some way to El Niño, but the patterns are not as well understood. Recently, researchers have used measured patterns of sea-surface temperatures to force atmospheric models. The striking result is that the history of the Dust Bowl is simulated rather accurately and seems to result from subtle, degree-or-less anomalies in the Pacific temperatures. Similarly, African Sahelian drought of previous decades may be explained by sea-surface-temperature anomalies in nearby oceans, with a little help from the effects of pollution on weather patterns[12].

NOW WHAT?

So what is one to make of all of this? People are affected by climate, but still manage to live in climates ranging from the frozen Arctic to the steamy tropics. Humans survived past climate changes and will survive changes in the future, but those past changes often caused great difficulties, and we are justified in worrying about future changes. We are rapidly pushing Earth's climate in a new direction by fundamentally changing the environment through activities such as cutting forests, damming rivers, paving landscapes, and burning fossil fuels. We will not be able to precisely predict all the changes this will bring, but it is highly likely that average global temperatures will be higher, with consequent changes such as sea-level rises. How much warmer probably depends mostly on whether we get serious about finding alternatives to burning fossil fuels to reduce the build-up of atmospheric carbon dioxide. Such alternatives might include energy conservation, switching to non-carbon-producing energy sources, and sequestration of carbon dioxide captured at the source or from the atmosphere[13].

Looking back, we find that temperatures have risen as carbon dioxide in the atmosphere has increased (see Figure 2). The greenhouse gas effect of carbon dioxide provides the best explanation of those temperature changes, supporting future projections of a warmer climate. 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 abrupt changes can be explained by mechanisms that appear to have brought the climate system to a threshold, after which the climate changed rapidly, often in a surprising direction. As we face a future of great change, it is worth remembering this past strange behavior and the possibility that we might trigger an abrupt change that could present more of a challenge than a gradual change. It also seems prudent to include the possibility of such strangeness, of abrupt climate change, in assessing what if anything should be done about the production of greenhouse gases.

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 convinces me that there is much more to learn, and I encourage students to pursue research in this area. I am struck by how important the oceans have been in this story; putting a freshwater and sea-ice cap on the North Atlantic has repeatedly arrested the Asian monsoon, and even subtle changes in Pacific temperatures have contributed to massive social

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[11] Cole, J.E., J.T. Overpeck, and E.R. Cook, 2002, Multiyear La Niña events and persistent drought in the contiguous United States, *Geophysical Research Letters* 29(13), doi10.1029/2001GL013561, no. 1647.

[12] Schubert, S.D., M.J. Suarez, P.J. Pegoin, R.D. Koster, and J.T. Bacmeister, 2004, On the cause of the 1930s Dust Bowl, *Science* 303(5565), 1855-1859; Giannini, A., R. Saravanan, and P. Chang, 2003, Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302(5647), 1027-1030; and Rotstayn, L.D., and U. Lohmann, 2002, Tropical rainfall trends and the indirect aerosol effect, *Journal of Climate* 15(15), 2103-2116.

[13] Lackner, K.S., 2003, A guide to CO_2 sequestration, Science 300(5626), 1677-1678; Broecker, W.S., 2003, *Fossil Fuel CO_2 and the Angry Climate Beast*, Eldigio Press, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York.

disruption thousands of miles away.

I remain optimistic about society's ability to address the environmental challenges arising from climate change. We have faced a great range of previous environmental problems, responding globally to the ozone hole and regionally to phosphate pollution in Lake Erie. Good ideas have often had unexpected consequences (new refrigerants and ozone destruction, or better detergents and overfertilization of lake ecosystems). As I remember, 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: (1) there really isn't a problem, and (2) if there is a problem, nature is doing it, not humans, and besides, (3) it would be too expensive to clean up the problem, anyway. Soon after, however, a novel solution appeared (low-phosphate detergents, or ozone-friendlier refrigerants), the problem was greatly reduced or eliminated at relatively low cost, new industries or products provided employment and contributed to the economy, and we are left wondering why we thought the problem would be so hard to fix. Other such environmental threats, including the effects of DDT on bird eggs, acid rain, and lead from gasoline, also have been reduced with much less pain and agony than some predicted. 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 would never consider going back to the old "look out below" system of dumping chamber pots out the window, but real investments were required to get indoor plumbing, sewers, and sewage-treatment plants—a sanitation system that remains 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 suit themselves. Professionals will prosper in new industries developed to meet the challenge of managing greenhouse gases. This is not a scientific judgment 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 should foster the genius of humanity to understand energy options and engineering, to devise new technologies, 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.

ACKNOWLEDGEMENTS

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FIGURE SOURCES

The figures use data from many sources. The data all are held at the IGBP PAGES/World Data Center for Paleoclimatology. NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, USA, available online at: http://www.ngdc.noaa.gov/paleo. This is one of the great resources of our field, and I am happy to acknowledge my debt to them. Figure 1 is a public-domain image from their slide set on ice cores, and was taken by Ken Abbott of the University of Colorado-Boulder. Figure 2 shows data from the Vostok, East Antarctica, from the paper by Petit J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.M. Barnola, I. Basile, M. Bender, J. Chappellaz, J. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V. Lipenkov, C. Lorius, L. Pipin, C. Ritz, E. Saltzman, and M. Stievenard, 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* 399, 429-436. The estimated South Pole sunshine is from Berger, A., and M.F. Loutre, 1991, Insolation values for the climate of the last 10 million years, *Quaternary Sciences Reviews* 10, 297-317. Figure 3 includes future changes in CO_2 from the Intergovernmental Panel on Climate Change, see note 7. Figures 4-6 include data from Alley, R.B., D.A. Meese, C.A. Shuman, A.J. Gow, K.C. Taylor, P.M. Grootes, J.W.C. White, M. Ram, E.D. Waddington, P.A. Mayewski, and G.A. Zielinski, 1993, Abrupt increase in snow accumulation at the end of the Younger Dryas event, *Nature* 362, 527-529; and from Grootes, P.M., and M. Stuiver, 1997, Oxygen 18/16 variability in Greenland snow and ice with 10^{-3}- to 10^{5}-year time resolution, *Journal of Geophysical Research* 102, 26455-26470, as calibrated by Cuffey, K.M. and G.D. Clow, 1997, Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition, *Journal of Geophysical Research* 102, 26383-26396. The cave data in Figure 6 are from 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, 2345-2348. I took the picture in Figure 7 with Gary Comer and George Denton in East Greenland, and thank them for their help. Figure 8 was prepared by Byron Parizek using data from NGDC and USGS.