Abrupt Climate Change

By Richard B. Alley

In the Hollywood disaster thriller *The Day after Tomorrow,* a climate catastrophe of ice age proportions catches the world unprepared. Millions of North Americans flee to sunny Mexico as wolves stalk the last few people huddled in freeze-dried New York City. Tornadoes ravage California. Giant hailstones pound Tokyo.

Are overwhelmingly abrupt climate changes likely to happen anytime soon, or did Fox Studios exaggerate wildly? The answer to both questions appears to be yes. Most climate experts agree that we need not fear a full-fledged ice age in the coming decades. But sudden, dramatic climate changes have struck many times in the past, and they could happen again. In fact, they are probably inevitable.

Inevitable, too, are the potential challenges to humanity. Unexpected warm spells may make certain regions more hospitable, but they could magnify sweltering conditions elsewhere. Cold snaps could make winters numbingly harsh and clog key navigation routes with ice. Severe droughts could render once fertile land agriculturally barren. These consequences would be particularly tough to bear because climate changes that occur suddenly often persist for centuries or even thousands of years. Indeed, the collapses of some ancient societies—once attributed to social, economic and political forces—are now being blamed largely on rapid shifts in climate.

The specter of abrupt climate change has attracted serious scientific investigation for more than a decade, but it has only recently captured the interest of

Winter temperatures plummeting six degrees Celsius and sudden droughts scorching farmland around the globe are not just the stuff of scary movies. Such striking climate jumps have happened before—sometimes within a matter of years

SLIM FILMS

SUDDEN FLIP-FLOPS are an unavoidable element of earthly climate.

filmmakers, economists and policymakers. Along with more attention comes increasing confusion about what triggers such change and what the outcomes will be. Casual observers might suppose that quick switches would dwarf any effects of human-induced global warming, which has been occurring gradually. But new evidence indicates that global warming should be more of a worry than ever: it could actually be pushing the earth's climate faster toward sudden shifts.

Jumping Back and Forth

SCIENTISTS MIGHT NEVER have fully appreciated the climate's ability to lurch into a radically different state if not for ice cores extracted from Greenland's massive ice sheet in the early 1990s. These colossal rods of ice—some three kilometers long—entomb a remarkably clear set of climate records spanning the past 110,000 years. Investigators can distinguish annual layers in the ice cores and date them using a variety of methods; the composition of the ice itself reveals the temperature at which it formed.

Such work has revealed a long history of wild fluctuations in climate—long deep freezes alternating with brief warm spells. Central Greenland experienced cold snaps as extreme as six degrees Celsius in just a few years. On the other hand it achieved roughly half of the heating sustained since the peak of the last ice age—more than 10 degrees C—in a mere decade. That jump, which occurred about 11,500 years ago, is the equivalent of Minneapolis or Moscow acquiring the relatively sultry conditions of Atlanta or Madrid.

Not only did the ice cores reveal what happened in Greenland, but they also hinted at the situation in the rest of the world. Researchers had hypothesized that the 10-degree warming in the north was part of a warming episode across a broad swath of the Northern Hemisphere and that this episode enhanced precipitation in that region and far beyond. In Greenland itself, the thickness of the annual ice layers showed that, indeed, snowfall had doubled in a single year. Analyses of old air bubbles caught in the ice corroborated the prediction of increased wetness in other areas. In particular, measurements of methane in the bubbles indicated that this swamp gas was entering the atmosphere 50 percent faster during the intense warming than it had previously. The methane most likely entered the atmosphere as wetlands flooded in the tropics and thawed up north.

The cores also contained evidence that helped scientists fill in other details about the environment at various times. Ice layers that trapped dust from Asia indicated the source of prevailing winds, for instance. Investigators concluded that the winds must have been calmer during warm times because less wind-blown sea salt and ash from faraway volcanoes accumulated in the ice. And the list of clues goes on [see "Greenland Ice Cores: Frozen in Time," by Richard B. Alley and Michael L. Bender; Scientific American, February 1998].

Intense, abrupt warming episodes appeared more than 20 times in the Greenland ice records. Within several hundreds or thousands of years after the start of a typical warm period, the climate reverted to slow cooling followed by quick cooling over as short a time as a century. Then the pattern began again with another warming that might take only a few years. During the most extreme cold conditions, icebergs strayed as far south as the coast of Portugal. Lesser challenges probably drove the Vikings out of Greenland during the most recent cold snap, called the Little Ice Age, which started around A.D. 1400 and lasted 500 years.

Sharp warm-ups and cool-downs in the north unfolded differently elsewhere in the world, even though they may have shared a common cause. Cold, wet times in Greenland correlate with particularly cold, dry, windy conditions in Europe and North America; they also coincide with anomalously warm weather in the South Atlantic and Antarctica. Investigators pieced together these regional histories from additional clues they found in the ice of high mountain glaciers, the thickness of tree rings, and the types of pollen and shells preserved in ancient mud at the bottoms of lakes and oceans, among other sources.

The evidence also revealed that abrupt shifts in rainfall have offered up challenges rivaling those produced by tem-

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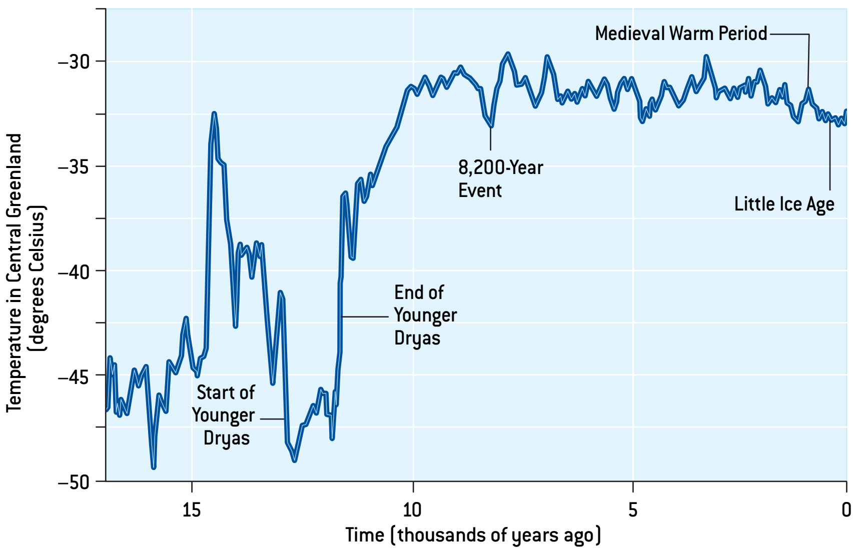
Overview/*Inevitable Surprises*

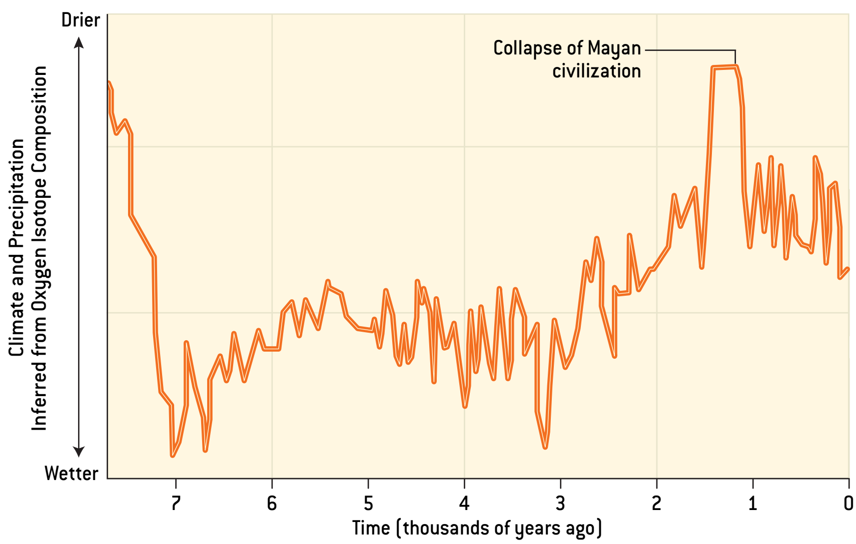
- Most climate change policy discussions and research efforts center on global warming. But another problem looms as well: climate has suddenly flip-flopped in the past and will surely do so again.
- A regional drought could, for instance, arrive one summer and stay for decades, wiping out rich agricultural lands across Asia and North America; weather patterns in Europe could shift in a matter of years, making that area's climate more like Siberia's.
- Scientists cannot yet predict when such abrupt changes will occur, but most climate experts warn that global warming and human activities may be propelling the world faster toward sudden, long-lasting climate changes.

PAST AS PROLOGUE?

Abrupt climate change has marked the earth's history for eons. Ice cores from Greenland, for instance, reveal that wild temperature swings (*top left*) punctuated the gradual warming that brought the planet out of the last ice age starting about 18,000 years ago. Fossil shells in lake sediments from Mexico's Yucatán Peninsula record sudden and severe droughts (*bottom left*) because a diagnostic ratio of oxygen isotopes in the shells shoots up when more water evaporates from the lake than falls as rain. Societies have often suffered as a result of these rapid shifts (*photographs*).



Viking settlement, now in ruins, was among those in Greenland abandoned during an abrupt cold spell called the Little Ice Age.



Mayan rain god (*statue in foreground*) was apparently no match for the drought now widely blamed for the collapse of Mayan civilization about 1,100 years ago.

ELIZA JEWETT; SOURCES: M. STUIVER ET AL. AND K. CUFFEY ET AL. (*top graph*) AND D. HODELL ET AL. (*bottom graph*) *National Geophysical Data Center*; RUDY BRUEGGEMANN (*top photo*); FREELANCE CONSULTING SERVICES PTY LTD/CORBIS (*bottom photo*)

perature swings. Cold times in the north typically brought drought to Saharan Africa and India. About 5,000 years ago a sudden drying converted the Sahara from a green landscape dotted with lakes to the scorching, sandy desert it is today. Two centuries of dryness about 1,100 years ago apparently contributed to the end of classic Mayan civilization in Mexico and elsewhere in Central America. In modern times, the El Niño phenomenon and other anomalies in the North Pacific occasionally have steered weather patterns far enough to trigger surprise droughts, such as the one responsible for the U.S. dust bowl of the 1930s.

Point of No Return

BE THEY WARM SPELLS, cold snaps or prolonged droughts, the precipitous climate changes of the past all happened for essentially the same reason. In each case, a gradual change in temperature or other physical condition pushed a key driver of climate toward an invisible threshold. At the point that threshold was crossed, the climate driver—and thus the climate as well—flipped to a new and different state and usually stayed there for a long time [*see box on next page*].

Crossing a climate threshold is similar to flipping a canoe. If you are sitting in a canoe on a lake and you lean gradually to one side, the canoe tips, too. You are pushing the canoe toward a threshold—the position after which the boat

CROSSING THE THRESHOLD

Global warming alters ambient conditions little by little. But even this kind of slow, steady change can push climate drivers, such as well-established ocean currents or patterns of rainfall, to a critical point at which they lurch abruptly into a new and different state. That switch brings with it an associated shift in climate—with potentially challenging consequences to people and societies. Once a climate driver crosses its so-called threshold, the changes that ensue could persist for millennia. Many thresholds may still await discovery; here are three that scientists have identified:

CLIMATE DRIVER	THRESHOLD CROSSING	RESULTING CLIMATE SHIFT	SOCIAL CONSEQUENCES
Ocean currents in the North Atlantic carry warmth northward from tropics, keeping western Europe's winters mild (*see box on opposite page*).	Freshening of surface waters in the far north slows down these currents, possibly stopping them altogether.	Temperatures plummet in the region, and climate in Europe and the eastern U.S. becomes more like Alaska's.	Agriculture suffers in regions around the world, and key navigation routes become clogged with ice.
Rainwater that is recycled through plants (absorbed by their roots and returned to the air through evaporation from their leaves) provides much of the precipitation in the world's grain belts.	A minor dry spell wilts or kills too many plants, and recycled rainfall disappears, reinforcing the drying in a vicious cycle.	A potentially mild dry spell is enhanced and prolonged into a severe drought.	Parched land can no longer support crops; famine strikes those who cannot trade for the remaining grain in the world market.
Currents in the Pacific Ocean determine major patterns of sea-surface temperature, which in turn control regional weather patterns.	Natural phenomena, such as El Niño, cause subtle changes in sea-surface temperatures, although scientists are still not sure why.	Weather patterns on adjacent continents shift, triggering severe storms or droughts where they typically do not occur.	Some croplands dry up while other places incur damage from intense storms.

can no longer stay upright. Lean a bit too far, and the canoe overturns.

Threshold crossings caused history's most extreme climate flips—and point to areas of particular concern for the future. To explain the icy spells recorded in Greenland's ice cores, for example, most scientists implicate altered behavior of currents in the North Atlantic, which are a dominant factor in that region's long-term weather patterns.

Eastern North America and Europe enjoy temperate conditions (like today's) when salty Atlantic waters warmed by southern sunshine flow northward across the equator. During far northern winters, the salty water arriving from the south becomes cold and dense enough to sink east and west of Greenland, after which it migrates southward along the seafloor. Meanwhile, as the cooled water sinks, warm currents from the south flow northward to take its place. The sinking water thereby drives what is called a conveyor belt circulation that warms the north and cools the south.

Ice cores contain evidence that sudden cold periods occurred after the North Atlantic became less salty, perhaps because freshwater lakes burst through the walls of glaciers and found their way to the sea. Researchers identify this rush of freshwater as the first phase of a critical threshold crossing because they know freshening the North Atlantic can slow or shut off the conveyor, shifting climate as a result.

Diluted by water from the land, seawater flowing in from the south would become less salty and thus less dense, possibly to the point that it could freeze into sea ice before it had a chance to sink. With sinking stopped and the conveyor halted, rain and snow that fell in the north could not be swept into the deep ocean and carried away. Instead they would accumulate on the sea surface and freshen the North Atlantic even more. The conveyor then would stay quiet, leaving nearby continents with climates more like Siberia's [*see box on opposite page*].

Chilling Warmth

EIGHT THOUSAND YEARS have passed since the last of the biggest North Atlantic cold snaps. Could it be that humans are actually "leaning" in the right direction to avoid flipping the climate's canoe? Perhaps, but most climate experts suspect instead that we are rocking the boat—by changing so many aspects of our world so rapidly. Particularly worrisome are human-induced increases in atmospheric concentrations of greenhouse gases, which are promoting global warming [see "Defusing the Global Warming Time Bomb," by James Hansen; SCIENTIFIC AMERICAN, March; www.sciam.com/ontheweb].

The United Nations–sanctioned Intergovernmental Panel on Climate Change has predicted that average global temperatures will rise 1.5 to 4.5 degrees C in the next 100 years. Many computer models that agree with this assessment also predict a slowdown of the North Atlantic conveyor. (As ironic as it may sound, gradual warming could lead to a sudden cooling of many degrees.) Uncertainties abound, and although a new ice age is not thought credible, the resulting changes could be notably larger than they were during the Little Ice Age, when the Thames in London froze and glaciers rumbled down the Alps.

THE AUTHOR

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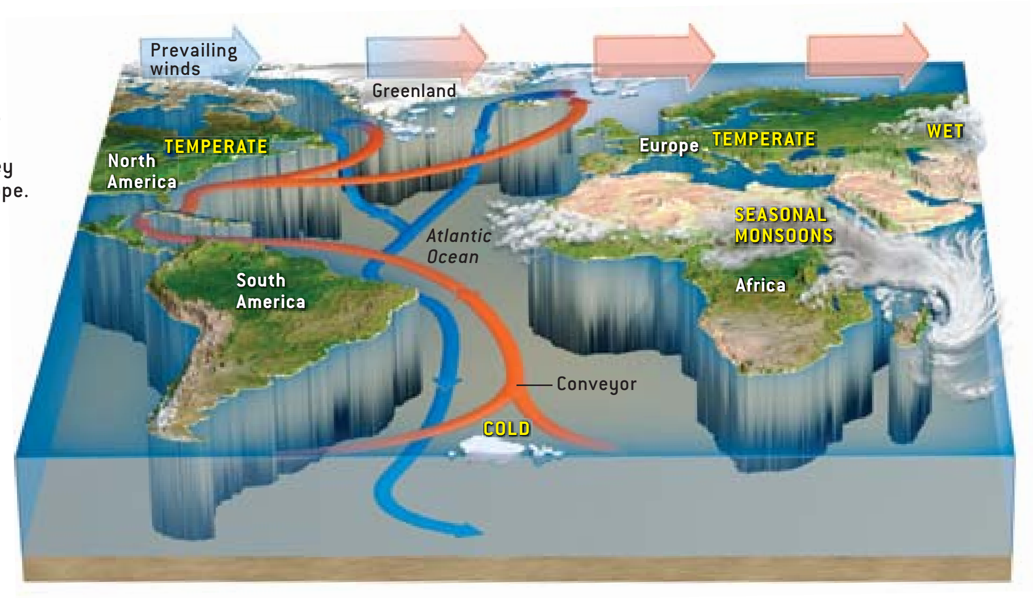
MELTING TOWARD A COLD SNAP?

As global warming continues to heat up the planet, many scientists fear that large pulses of freshwater melting off the Greenland ice sheet and other frozen northern landmasses could obstruct the so-called North Atlantic conveyor, the system of ocean currents that brings warmth to Europe and strongly influences climate elsewhere in the world. A conveyor shutdown—or even a significant slowdown—could cool the North Atlantic region even as global temperatures continue to rise. Other challenging and abrupt climate changes would almost certainly result.

CONVEYOR ON

Salty ocean currents (*red*) flowing northward from the tropics warm prevailing winds (*large arrows*) as they blow eastward toward Europe. The heat-bearing currents, which are dense, become even denser as they lose heat to the atmosphere. Eventually the cold, salty water becomes dense enough to sink near Greenland. It then migrates southward along the seafloor (*blue*), leaving a void that draws more warm water from the south to take its place.

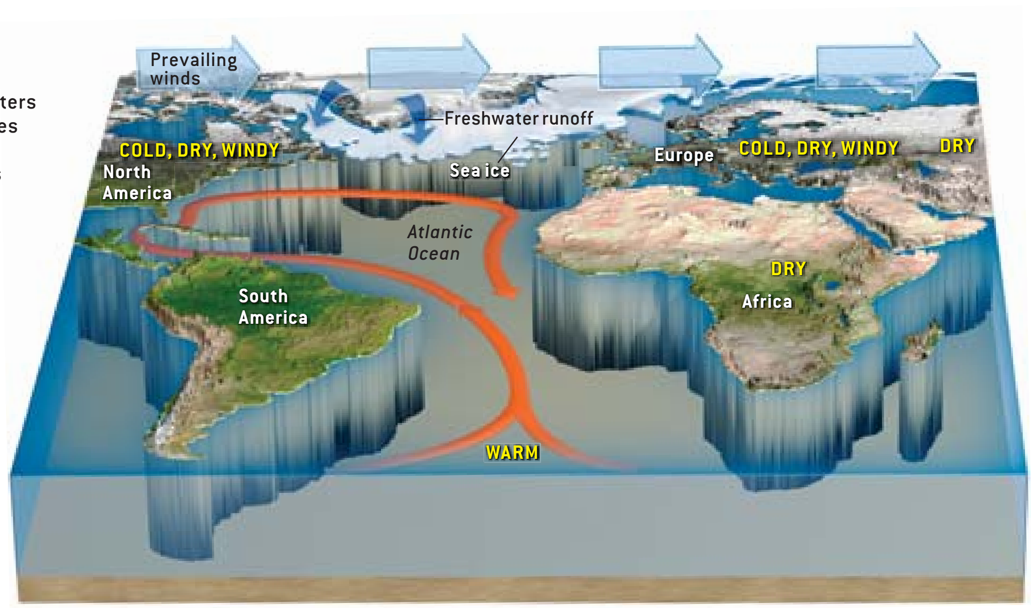


RESULTING CLIMATE

When the North Atlantic conveyor is active, temperate conditions with relatively warm winters enable rich agricultural production in much of Europe and North America. Seasonal monsoons fuel growing seasons in broad swaths of Africa and the Far East. Central Asia is wet, and Antarctica and the South Atlantic are typically cold.

CONVEYOR OFF

If too much freshwater enters the North Atlantic, it dilutes the salty currents from the south. Surface waters no longer become dense enough to sink, no matter how cold the water gets, and the conveyor shuts down or slows. Prevailing winds now carry frigid air eastward (*large arrows*). This cold trend could endure for decades or more—until southern waters become salty enough to overwhelm the fresher water up north, restarting the conveyor in an enormous rush.



RESULTING CLIMATE

As the conveyor grows quiet, winters become harsher in much of Europe and North America, and agriculture suffers. These regions, along with those that usually rely on seasonal monsoons, suffer from droughts sometimes enhanced by stronger winds. Central Asia gets drier, and many regions in the Southern Hemisphere become warmer than usual.

DAVID FIERSTEIN

Tricky Predictions

No credible predictions of abrupt climate changes have ever been issued—nor should you expect one anytime soon. That is because rapid changes are inherently more difficult to forecast than global warming or other gradual changes.

One major stumbling block has to do with the very nature of abrupt change. A rapid shift occurs when a slow but steady force, such as global warming, moves a crucial component of the climate system past a point of no easy return. Crossing such a threshold triggers a sudden switch to a new state—much the way leaning over too far in a canoe suddenly dumps you in the lake. Knowing exactly how far you can tip the canoe without overturning is almost impossible, however, especially as wind and waves rock the boat. Similarly, it is exceedingly tough to recognize when an aspect of climate is approaching a critical threshold.

Researchers have attempted to gain insight into the factors that operate near a tipping point through computer modeling. These efforts have revealed much about what rocks the climate's canoe, but uncertainties still abound. To determine how accurately their computer models will forecast climate change, scientists check to see how well the programs simulate real-world changes from the past. Many models match the basic types of previous climate anomalies reasonably well—in other words, they reliably reproduce cold spells or droughts or flooding at the locations and times that have been recorded in annual layers of ice and sediment. Some of them even do a decent job of simulating shifts in storm tracks, wind patterns, seasonal precipitation and other finer details.

But even if the models get the general nature of the climate change right, they represent important parameters imperfectly. In particular, the abrupt changes of the past were usually larger and more widespread than the models indicate. Most of them underestimate the amount of moisture lost in the Sahara over the past few thousand years, for example. The models also seem to have trouble simulating both the great warmth of the polar regions during the time of the dinosaurs and the extreme cold at the peak of the most recent ice age.

The simplest reason for these mismatches may be that the models are typically less sensitive than the climate is, perhaps because they omit key feedbacks and responses. Climate thresholds that no one has yet considered might also explain the discrepancies. Locating these thresholds would undoubtedly prove helpful, even though more potential climate flips could be unveiled in the process. On the bright side, new discoveries might instead reveal that the likelihood for abrupt change is actually lower than scientists suspect or that one change might offset another. *—R.B.A.*

BALANCING ACT: The earth typically experiences a given climate for millennia or more. Then, at a moment that is nearly impossible to predict, some aspect of the climate system teeters too far to one side and global conditions tumble into a starkly different state.

Perhaps of greater concern than cold spells up north are the adverse effects that would probably strike other parts of the world concurrently. Records of climate across broad areas of Africa and Asia that typically benefit from a season of heavy monsoons indicate that these areas were particularly dry whenever the North Atlantic region was colder than the lands around it. Even the cooling from a conveyor slowdown might be enough to produce the drying. With billions of people relying on monsoons to water crops, even a minor drought could lead to widespread famine.

The consequences of future North Atlantic freshening and cooling may make life more difficult even for people living in regions outside the extreme cold or drought. Unease over such broad impacts spurred the U.S. Department of Defense to request that a think tank called the Global Business Network assess the possible national security implications of a total shutdown of the North Atlantic conveyor. Many scientists, including me, think that a moderate slowdown is much more likely than a total shutdown; either way, the seriousness of the potential outcome makes considering the worst-case implications worthwhile. As the Global Business Network report states, "Tensions could mount around the world.... Nations with the resources to do so may build virtual fortresses around their countries, preserving resources for themselves. Less fortunate nations ... may initiate in struggles for access to food, clean water, or energy."

Floods and Droughts

EVEN IF A SLOWDOWN of the North Atlantic conveyor never happens, global warming could bring about troubling threshold crossings elsewhere. The grain belts that stretch across the interiors of many midlatitude continents face a regional risk of prolonged drought. Most climate models produce greater summertime drying over these areas as average global temperatures rise, regardless of what happens in the North Atlantic. The same forecasts suggest that greenhouse-induced warming will increase rainfall overall, possibly in the form of more severe storms and flooding; however, those events—significant problems on their own—are not expected to offset the droughts.

Summer drying could cause a relatively mild drought to worsen and persist for decades or more. This transition would occur because of a vulnerability of the grain belts: for precipitation, they rely heavily on rainfall that local plants recycle rather than on new moisture

MATT COLLINS

blown in from elsewhere. The plants' roots normally absorb water that would otherwise soak through the ground to streams and flow to the sea. Some of that water then returns to the air by evaporating through their leaves. As the region begins to suffer drier summers, however, the plants wilt and possibly die, thereby putting less water back into the air. The vital threshold is crossed when the plant population shrinks to the point that the recycled rainfall becomes too meager to sustain the population. At that point more plants die, and the rainfall diminishes further—in a vicious cycle like the one that turned the Sahara into a desert 5,000 years ago. The region has shown no signs of greening ever since.

Scientists fear they have not yet identified many of the thresholds that, when crossed, would lead to changes in regional climates. That knowledge gap is worrisome, because humans could well be doing many things to tip the climate balance in ways we will regret. Dancing in a canoe is not usually recommended, yet dance we do: We are replacing forests with croplands, which increases how much sunlight the land reflects; we are pumping water out of the ground, which changes how much water rivers carry to the oceans; and we are altering the quantities of trace gases and particulates in the atmosphere, which modifies the characteristics of clouds, rainfall and more.

Facing the Future

NEGATIVE CONSEQUENCES of a major climate shift can be mitigated if the change occurs gradually or is expected. Farmers anticipating a drought can drill wells, or learn to grow crops less dependent on water, or simply cut their losses and move elsewhere. But unexpected change can be devastating. A single, surprise drought year may at first bankrupt or starve only the most marginal farmers, but damage worsens as the drought lengthens—especially if no one had time to prepare. Unfortunately, scientists have little ability to predict when abrupt climate change will occur and what form it will take [*see box on opposite page*].

Despite the potentially enormous consequences of a sudden climate transformation, the vast majority of climate research and policymaking has addressed gradual shifts—most notably by calling for global reductions of carbon emissions as a way to slow the gradual rise in global temperatures. Although such reductions would probably help limit climate instability, thought should also be given specifically to avoiding abrupt changes. At one extreme, we might decide to ignore the prospect altogether and hope that nothing happens or that we are able to deal with whatever does happen; business-as-usual did sink the *Titanic,* but many other unprepared ships have crossed the North Atlantic unscathed. On the other hand, we might seriously alter our behavior to keep the human effects on climate small enough to make a catastrophic shift less likely. Curbing global warming would be a step in the right direction. Further investigation of climate thresholds and their vulnerabilities to human activities should illuminate other useful actions.

A third strategy would be for societies to shore up their abilities to cope with abrupt climate change before the next surprise is upon us, as suggested by the U.S. National Research Council. The authors of the council's report pointed out that some former societies have bent in response to climate change when others have broken. The Viking settlers in Greenland abandoned their weakening settlement as the onset of the Little Ice Age made their way of life marginal or unsustainable, while their neighbors, the Thule Inuit, survived. Understanding what separates bending from breaking could prove constructive. Plans designed to help ease difficulties if a crisis develops could be made at little or no cost. Communities could plant trees now to help hold soil during the next windy dry spell, for example, and they could agree now on who will have access to which water supplies when that resource becomes less abundant.

For now, it appears likely that humans are rocking the boat, pushing certain aspects of climate closer to the thresholds that could unleash sudden changes. Such events would not trigger a new ice age or otherwise rival the fertile imaginations of the writers of the silver screen, but they could pose daunting challenges for humans and other living things on earth. It is well worth considering how societies might increase their resiliency to the potential consequences of an abrupt shift—or even how to avoid flipping the climate canoe in the first place. SA

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MORE TO EXPLORE

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