24

Ocean Circulation: Conveyor of Past and Future Climate

Steven M. Stanley

The geological record tells of Earth's distant past—of mountains rising up and wasting away, of seas flooding continents and receding again, and of distinctive life forms arising and then vanishing to have their places taken by others. Our backward gaze educates and delights us, simply by connecting us with our deep roots, but history for its own sake is not all that geology is about. By studying the distant past, we come to understand how the world around us operates and how future changes wrought by humans may transform our planet and its inhabitants.

Earth's outer shell, together with its oceans and atmosphere, serves as a vast laboratory in which nature conducts experiments on a scale that we cannot faithfully mimic with our own, much simpler physical models and computer programs. Nature's laboratory has been up and running for more than four billion years, and its history has been continually archived through the accumulation of strata and fossils. Although this geological record is far from complete, we can decipher many of its key elements, and the results enlighten us about the functioning of environments and life. What follows is a discussion of one such deciphering. My story is about our global climate: how it has undergone a profound shift within the past few million years and how this vicissitude of the relatively recent geological past informs us about what may happen during the next few decades as human activities alter the natural world.[1]

This story is not confined to the field of geology. It has many geological aspects, some of them involving fossils, but it also entails basic concepts of oceanography and climatology. Such is the multidisciplinary nature of much research in the earth sciences these days. Our planet, its oceans, and its atmosphere interact continuously, and we are finally beginning to treat them as parts of a single system.

We live in an ice age. When I make this statement to an average, well-educated person, the response is disbelief. "I thought that the ice age ended thousands of years ago," is the typical reply. Not so, I explain. What ended was not the ice age but only the most recent glacial maximum, which is to say the most recent interval of glacial expansion. Although we live during an interval of glacial recession for the United States and Europe, an ice cap still blankets nearly all of Greenland; and in about 80,000 years, glaciers are scheduled once again to spread southward to New Jersey and the Alps. We can make this prediction because the ice age that now afflicts the northern hemisphere entails the expansion and contraction of glaciers at regular intervals—intervals dictated by periodic changes in aspects of Earth's rotation both on its axis and in its orbit. These so-called orbital factors change both the amount and the distribution of the solar heat that warms our planet.

Although the glacial fluctuations that result from Earth's orbital motions are environmentally significant, they are nonetheless an epiphenomenon. Far more profound was the global change that plunged the northern hemisphere into the modern ice age to begin with, slightly more than three million years ago—the event that ended a balmy interval and created the cooler climatic conditions that we humans view as normal because our species came into being long after they were in place. These climatic changes brought perennial winter to the northern polar region, where summers had previously been mild, and caused a persistent ice sheet to grow over Greenland, where vegetation had previously cloaked the land. The ice age in which we in North America live is actually best described as the modern ice age of the northern hemisphere, because an ice age that began much earlier in the southern polar region also persists today, and the northern hemisphere itself has experienced other ice ages much further back in Earth's history.

My central topic addresses the cause of this modern ice age of the north, but I will also extract from my explanatory scenario a dire prediction as to what may happen to our planet if we humans do not mend our ways. I will raise the prospect that human-induced environmental change may some decades hence send us plunging precipitously back into the pre-ice age world. The result would be global warming on a scale that scientists have not previously imagined.

A BALMY WORLD BEFORE THE GREAT FREEZING

The northern polar region is the key. Cold in the far north may seem natural from our present perspective, but the top of our planet has actually been bathed in temperate climates during most of the past half-billion years. And so it was before the modern ice age got underway about 3.3 million years ago. During this earlier time, early in the Pliocene Epoch (5.3 up to 1.8 million years ago) when our apelike ancestor nicknamed Lucy and her australopithecine relatives were gamboling about in Africa, the surface of the Dark Continent was even darker than today, because it was moister. Thus, forests and woodlands, which require considerable moisture, were more widespread than they are now, and savannas, which flourish under drier conditions, were less extensive. In fact, back then, many of Earth's terrestrial terrains received more rain than they do today because ocean temperatures were warmer, a condition that led to higher rates of evaporation of surface waters and transport of more moisture to continents. Seas also stood higher relative to continental surfaces than they do now because less of the planet's water was locked up in ice sheets.

Fossils provide abundant evidence of the widespread warmth that preceded the ice age. For example, where shallow seas spread westward beyond Virginia Beach to Petersburg, Virginia, fossils of marine life point to quite mild climates. Although summers there were perhaps no warmer than they are today, winter temperatures were some 9°F higher. Today it is the cold northern polar region that sends frigid air to midlatitudes in winter. Pre-ice age Virginia was obviously spared such icy Arctic blasts. The implication is that the Arctic region was much warmer then than it is today. In fact, there is direct evidence of this condition.

Iceland sits at the juncture between the Arctic and Atlantic oceans. When we understand certain geological indicators, this volcanic island serves as a huge thermometer protruding from the mouth of the Arctic Ocean—a thermometer on which we can read segments of the climatic history of the northern polar region. Rising along the northern shore of Iceland are cliffs of fossiliferous sediment that accumulated in shallow seas shortly before and during the onset of the ice age. Within these strata are so-called tills—gravelly bodies of sediment ploughed up by glaciers early in the history of the ice age. Sediments below the tills give evidence of much warmer climates than those under which glaciers can form. These lower sediments have yielded pollen of ancient coastal land plants that, judging from the requirements of close living relatives, lived in a temperate climate—one that yielded an average annual temperature some 9°F warmer than that of the present.

Fossil shells also abound in the strata of northern Iceland; and at a particular level as one ascends the cliffs, a flood of new species of bivalves, snails, and other forms of marine life appears. Remarkably, these are immigrants of Pacific origins that made their way through the Bering Strait to the Arctic Ocean and through the Arctic to the Atlantic. The most familiar among the Pacific arrivals is the blue mussel, the edible animal that now colonizes rocky shores of the northeastern United States and also Britain, where it is celebrated in the ballad about the vendor singing "Cockles and mussels alive, alive, Oh." The remarkable thing about some of the immigrants that made their way across the polar region is that they cannot tolerate the frigid conditions of the Arctic Ocean today—these are forms assigned to the thermal category for marine life known as cold temperate. Their passage through the Arctic Ocean has been dated at slightly more than 3 million years ago, which tells us that the Arctic at that time had a cold temperate climate. Fossil pollen from North America and Asia tells a similar story. Evergreen forests then grew where tundra now encircles the Arctic. Today, such forests are restricted to more southerly regions where the average July temperature is at least 50°F.

EXTINCTION TELLS OF COOLING

I have spent much time studying the fossil bivalve mollusks—clams, scallops, oysters, and mussels—that inhabited the Atlantic coastal waters of North America during the warm interval that preceded the modern ice age. My interest in this fauna was sparked by the observation that only about 30 percent of its species survive to the present day. This number is less than half the survival percentage for faunas of similar age in California and Japan. In other words, Pacific faunas have been more enduring. Central Florida yields rich fossil mollusk faunas; shells of species that lived slightly before the onset of the ice age are spectacularly preserved, many remaining shiny and some even retaining remnants of color patterns. This region, which is subtropical today, enjoyed a tropical climate before the extinction event. As happens in all marginally tropical regions, some of the species that occupied central Florida just before the ice age were restricted to the tropics, whereas others tolerated cooler conditions. While surveying these species some years ago, I discovered an arresting fact: All the strictly tropical ones were annihilated early in the modern ice age. Every one of the fossil species that survives today ranges well beyond the tropics, around the Gulf Coast to Texas or northward along the Atlantic Coast to the Carolinas. Clearly, the ability to tolerate cool temperatures was the key to survival.

Three great ice caps occupied the land during each glacial maximum of the modern ice age—one centered in eastern Canada, one in Greenland, and one in Scandinavia. These three large ice sheets fringed the North Atlantic Ocean, whereas none bordered the North Pacific. It is easy to see why cooling early in the ice age decimated the North Atlantic marine fauna, whereas the North Pacific fauna was little affected.

WHY AN ICE AGE?

The cause of the modern ice age has long been debated. During much of the last century, an even more fundamental debate raged within the science of geology. The very idea of an ice age seemed at variance with the new uniformitarian view of the planet, which held that all geological features are the products of processes that we can see operating today—volcanic eruptions, for example, and water movements that deposit sand along rivers and beaches, and earthquakes that rend and shift Earth's crust. How could it be that in times past great mountains of ice spread over regions where forests and cities now stand? To many scientists, a less far-fetched mechanism, such as an enormous flood, seemed preferable to account for the transport of boulders far from outcrops of their parent bedrock or for the emplacement of large mounds and sinuous ridges of gravelly sediment.

In time, the glacial hypothesis won out, thanks in part to the discovery in 1852 that ice covered all of Greenland, rather than being confined to its margins. This revelation that a continental ice cap existed in the modern world obviated the uniformitarian objection to the concept of continental glaciation. Then in 1875, geologists discovered scratches in limestone near Berlin that were indistinguishable from ones that had clearly been ground into bedrock in the Swiss Alps by small mountain glaciers. At about the same time, North American geologists traced an irregular rubbly ridge of sediment from Cape Cod to the Pacific Northwest. What could have erected such an extensive structure other than a vast, spreading glacier pushing before it soil, gravel, and boulders ploughed up while it ground southward? Soon geologists universally acknowledged that, quite recently in Earth's history, mountainous glaciers had beset large areas of the northern hemisphere. What followed was more than a century of puzzlement over the cause of this event.

This problem began gnawing at me about two decades ago when I began studying how the sudden chill of the ice age brought an end to the mild climate of eastern North America and wiped out many species of marine life that were ill-adapted to cold winters. Something discouraged me from theorizing about the cause of the ice age, however. This something was the possibility that simple greenhouse cooling was the culprit. The greenhouse effect results from the presence in Earth's atmosphere of certain gases, including carbon dioxide, that trap solar heat like the glass of a greenhouse. It seemed that, just as human burning of fossil fuels intensifies greenhouse warming by releasing carbon dioxide to the atmosphere, some natural change slightly more than three million years ago might have reduced the concentration of carbon dioxide in Earth's atmosphere, diminishing the greenhouse effect enough to cool our planet and trigger the ice age. Then, in 1994, a colleague reported on research ostensibly showing that the concentration of atmospheric carbon dioxide did not decline as the northern hemisphere plunged into the ice age—that greenhouse cooling was not the cause of this profound event. This research has since been discredited, but in 1994 it seemed to compel us to search beyond the greenhouse effect to explain the ice age. Clearly, then, we needed to seek an explanation that entailed changes in circulation patterns of the ocean and atmosphere—changes in the transport of heat, and perhaps moisture, above the solid Earth. Adopting this view, I began to dwell intently on the problem and soon pursued the following line of reasoning.

First, I concluded that a commonly entertained idea must be rejected. This is the notion that the modern ice age of the northern hemisphere began simply because something caused large glaciers to grow. If, for example, precipitation increased, then snow might have accumulated to such great depths over such broad northern regions that its compaction produced large glaciers. The problem here is one of temperature. Before the ice age began, the polar region was much too warm for snow to have persisted at low elevations in summer; and where snow melts in summer, glaciers cannot form. The entire polar region is much colder today than it was shortly before the ice age began; the transition to the colder, modern state is what permitted continental glaciers, including the persistent Greenland ice cap, to grow. In other words, whatever happened to replace the temperate (albeit cold temperate) climate of the far north with the modern Arctic climate was the trigger for the ice age.

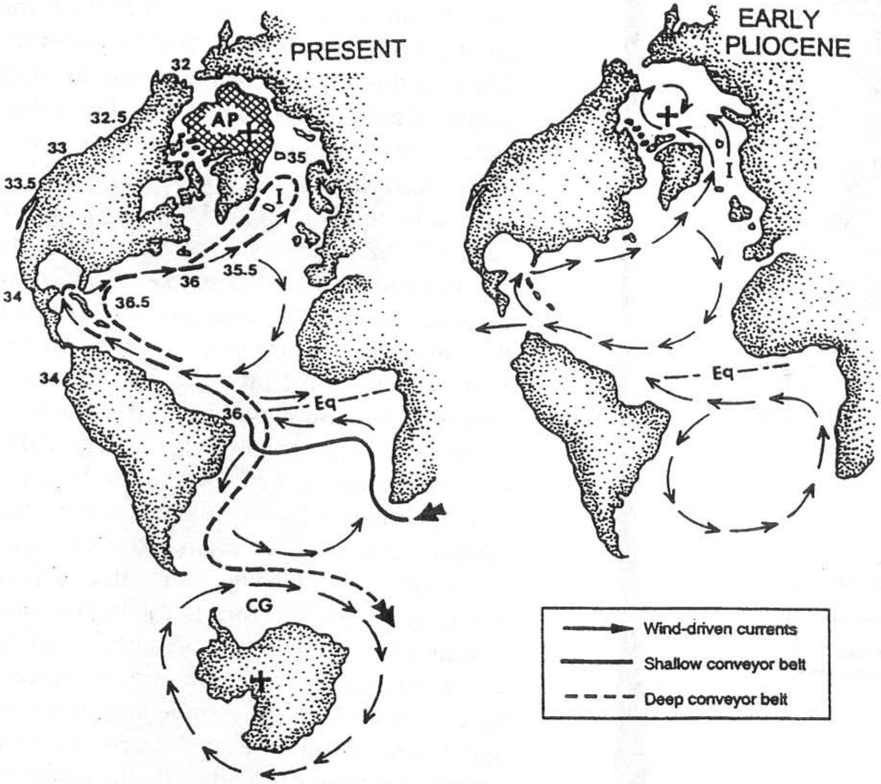
The next logical step was to ask what keeps the Arctic region cold today. If we can identify the present refrigeration system and show that it was set in place at the time when the ice age began, then we have an explanation for the ice age.

THE ARCTIC OCEAN IS THE KEY

In the course of geologic time, the Arctic Ocean and the polar atmosphere warm and cool in unison because of their juxtaposition. Because of the high heat capacity of water—that is, its ability to hold heat—we should look to the Arctic Ocean, rather than the polar atmosphere, as the body of fluid that controls the temperature of both. The point is that it takes an enormous mass of air to cool a body of water the size of the Arctic Ocean substantially. On the other hand, a cold Arctic Ocean can easily refrigerate a sizable portion of Earth's atmosphere.

I have come to refer to the upper layer of the Arctic Ocean as the Arctic pond, because it experiences only a weak interchange of water with the Pacific and the Atlantic. The Arctic pond remains cold today because it receives no strong inflow of warm water from the south. It simply assumes the very cold temperature that will characterize any largely isolated body of water in a polar region, where the sun's rays arrive at a low angle. Because of their relative isolation from the rest of the world's oceans, the waters of the Arctic pond are strongly diluted by inflow from large Siberian rivers; thus, they are brackish—or less salty than typical seawater.

Iceland sits near the middle of a broad strait between the Arctic Ocean and the Atlantic. Currents derived from the Gulf Stream carry warm waters northeastward toward this passageway, and they might be expected to flow into the Arctic Ocean, bringing with them much heat. Surprisingly, however, the currents do not continue northward but instead sink to great depths just north of Iceland and double back to the south, eventually surfacing again in the Pacific. By looping downward at the brink of the Arctic Ocean, the Atlantic waters deprive the upper portion of the polar ocean of their warmth. The result is the frigid Arctic pond.



A comparison of northern oceans today and early in the Pliocene Epoch, before the onset of the modern ice age of the northern hemisphere. In the modern world (left), the conveyor belt flow carries surface waters (heavy line) from the Pacific, around the tip of Africa, and through the Caribbean, where they join a wind-driven current (slender arrows) and pass poleward until they sink north of Iceland (I). The submerged conveyor belt waters (dashed line) flow back to the south along a similar course, returning to the Pacific. Largely isolated from the warm Atlantic, the upper waters of the Arctic, which are diluted by river water, form the cold Arctic pond (AP). Numbers in the oceans indicate the salt content of seawater, in parts per thousand; they show that evaporation by the dry trade winds concentrates the conveyor belt waters north of the Equator (Eq), which is why they sink after flowing to the far north, where cooling also increases their density. Pacific waters are less salty, in part because of dilution by water that the trade winds carry across the Isthmus of Panama from the Atlantic. At the other end of the planet, the Circumantarctic Gyre (CG) encircles Antarctica.

Early in Pliocene time (right), before the Isthmus of Panama formed, flow between the Atlantic and Pacific oceans would have kept the waters of these oceans relatively well mixed and similar in salt content. Atlantic waters would not have been dense enough to sink north of Iceland and drive the conveyor belt as they do today, but a wind-driven current would nonetheless have flowed northward through the Atlantic. Being relatively buoyant, the waters of this current should have passed into the Arctic Ocean and warmed it, probably sinking near the North Pole (+) after cooling. The heat that they transported to the Arctic Ocean should have warmed the entire polar region, thereby causing winters here and at middle latitudes to be much warmer than they are today.

THE ROLE OF THE CONVEYOR BELT

The Atlantic waters that descend at the brink of the Arctic Ocean form a segment of the great ribbon of moving water dubbed the oceanic conveyor belt. Waters of the conveyor belt rise up in the middle of the Pacific Ocean and flow westward around the tip of Africa. From there, the conveyor belt flows diagonally across the Atlantic, through the Caribbean, and then poleward. Portions of the conveyor belt, including the segment known as the Gulf Stream, are pushed by the wind, but the main driver of the conveyor belt is its descent north of Iceland under the influence of gravity.

The conveyor belt's waters eventually sink in the north because they have become cool and therefore dense. But this is clearly not the only reason for their descent, because surface waters of the northernmost Pacific are just as cool as those of the northernmost Atlantic, and yet they remain buoyant. A second factor also comes into play: North Atlantic waters are saltier, or more saline, than typical seawater. The high density that causes them to sink and drive the conveyor belt results in part from their cold temperature and in part from their high salt content. They sink in the region where they meet the more buoyant waters at the margin of the Arctic pond.

Because the conveyor belt that deprives the Arctic Ocean of Atlantic warmth owes its existence to the high salinity of the conveyor belt waters, the question that jumps out is whether something may have happened to elevate the salt content of the North Atlantic waters slightly before three million years ago, when the ice age got underway. This would be the event that led to the ice age. To answer this question, we must consider what makes the conveyor belt waters so salty in the North Atlantic region today. Maps depicting the distribution of salinity in this ocean show that the buildup of salt occurs at low latitudes, where the dry trade winds, sweeping westward from the Sahara Desert, evaporate water from the sea surface. Some of the water that the trade winds pick up is dumped in Central America, as monsoon rains, but some of it finds its way to the eastern Pacific Ocean, where it dilutes the surface waters. In other words, the trade winds transfer water from the Atlantic to the Pacific. Thus, as the waters of the conveyor belt pass through the zone of the trade winds, they become more concentrated—more salty. Although these waters become slightly diluted by river water as they move northward, in the area where they descend, just north of Iceland, their salinity remains slightly above the average for seawater.

What might have happened slightly more than three million years ago to initiate the pattern of water movement that makes the Atlantic unusually salty? To answer this question, it is logical to focus on Central America, where the transfer of water to the Pacific takes place. As it turns out, before the ice age began, this region had a very different geographical configuration than it has today. In fact, the Isthmus of Panama did not yet exist. In its place was an oceanic strait connecting the Atlantic and the Pacific. Because of Earth's rotation, winds and currents sweep westward in the equatorial regions of both the Atlantic and the Pacific oceans. When a gap existed between North and South America, the Atlantic equatorial current would have carried saltier-than-normal water of the trade wind belt into the Pacific. Compensating for this exodus of water from the Atlantic would have been a flow of water in the opposite direction—from the Pacific to the Atlantic—deep beneath the ocean's surface. In short, with the two great oceans connected by a sizable strait, their waters would have been relatively well mixed. As a result, their salinities would have been more nearly in balance than they are today; for its part, the Atlantic would have been less saline. All of this had to change when the Isthmus of Panama came into being.

Lo and behold, the modern ice age began at just about the time the isthmus formed. Strange as it may seem, sediment obtained by drilling the floor of the deep sea provides the best means of dating the early stages of the ice age. Cores of deep-sea sediment contain shell-like skeletons of tiny fossil plankton, and the isotopic composition of oxygen in these skeletons records the expansion of glaciers on the land. The basic principles here are easily grasped.

Oxygen comes in two isotopic forms. These are stable isotopes; unlike the radioactive isotopes of some other elements, they do not decay spontaneously. An atom of oxygen-18 contains two more neutrons than an atom of oxygen-16 and is therefore heavier. Water molecules at the surface of the ocean that contain an oxygen-16 atom move into the atmosphere through evaporation more readily than water molecules that contain the heavier isotope, oxygen-18. The result is that the water vapor in clouds that form above the ocean is isotopically lighter than the water below. When such clouds move over a cold landmass and release their moisture as snow, the snow also contains a disproportionately large amount of light oxygen. As a result, when glaciers build up on the land, acting as huge new storage tanks, they sequester from the global hydrologic cycle water that is enriched in oxygen-16. In complementary fashion, the water remaining in the ocean is relatively enriched in heavy oxygen. The result is that organisms that secrete skeletons of calcium carbonate, each molecule of which contains three oxygen atoms, assimilate more heavy oxygen from the surrounding water. When scientists work upward through a deep-sea core, measuring the relative amounts of the two oxygen isotopes in the fossil skeletons of fossil plankton, a pronounced shift toward the heavier isotope generally signals the expansion of glaciers. (Actually, such a shift is magnified by another aspect of skeletal secretion: The relative amount of the heavier isotope incorporated into the skeletons of organisms increases as the temperature of their watery world declines, as it does in many regions at times when glaciers are expanding.)

When the ice age began, oxygen isotopes in seawater began to fluctuate systematically, with reversals occurring every few tens of thousands of years as glacial maxima alternated with glacial minima. A variety of techniques, including dating methods based on the decay of naturally occurring radioactive isotopes, reveal that these fluctuations—and, hence, the ice age—commenced a little more than three million years ago.

The closure of the strait between the Americas cannot be pinned down so precisely in time, in part because it was a somewhat protracted event. The sliver of Earth's crust that now forms the isthmus came into being in the eastern Pacific Ocean millions of years before reaching its present position. It rose up from the floor of the deep sea as an array of volcanic islands. During a regional shifting of vast plates of Earth's outer shell, this group of islands slid eastward to lodge between the Americas. There is geological evidence that the volcanic islands formed a partial barrier more than four million years ago. Fossils, however, reveal that mollusks adapted to shallow water did not become widespread in Panama and Costa Rica until sometime between 3.5 and 3 million years ago; it must have been during this interval that the building of the isthmus was completed. This, then, is when the modern conveyor belt should have been set in motion.

What was the configuration of the Atlantic and Arctic oceans before the Isthmus of Panama wrought its changes? Although the wind-driven Gulf Stream would inevitably have been present, it would have flowed more weakly than today because it lacked the supplemental driving force of the modern conveyor belt. I use the label "modern conveyor belt" because waters may have descended north of Iceland, but closer to the pole than they do today—somewhere in the Arctic Ocean where the waters carried north by the Gulf Stream eventually became cool enough to sink. The key point is that Atlantic waters would not have been dense enough to sink at the brink of the Arctic Ocean, where they do today, and their continued northward flow would have brought much heat to this polar ocean. Here, I believe, is the explanation for the warmth of the pre-ice age Arctic region that we see evidenced by fossil land plants and marine animals.

All this changed when the Isthmus of Panama came into being. The Atlantic Ocean became saltier, and the modern conveyor belt formed, leaving the upper Arctic Ocean only weakly connected to the warm Atlantic and allowing it to cool down in its polar isolation. Here is how we can date the conveyor belt's origin and connect it to that of the isthmus.

The southward-flowing segment of the conveyor belt has deposited sediments in the deep sea, and fossils within these sediments indicate that they began to accumulate slightly before three million years ago. Fossil plankton reveal that the high salinity of the Atlantic—the driving force of the conveyor belt—also appeared at about this time. An isotopic shift toward heavier oxygen in the skeletons of these creatures occurred between four and three million years ago in the Caribbean Sea, along the path of the modern conveyor belt. This region remained warm, however, and large glaciers had not yet grown on northern continents, so the isotopic shift for the Caribbean cannot be attributed to climatic cooling or glacial expansion. The shift must instead have resulted from an entirely different kind of change: increased salinity of Atlantic waters. As we have seen, evaporation preferentially removes isotopically light water molecules from the upper ocean. The shift toward isotopically heavier water in the Caribbean, reflected in the skeletons of plankton, must have resulted from export to the Pacific of the light water that evaporated from the Atlantic. This export was possible only after the strait between North and South America became blocked and the barrier prevented mixing of the two oceans—the Pacific had to retain the water that the trade winds carried to it across the Isthmus of Panama from the Atlantic. The implication is that the Isthmus of Panama became an effective barrier between four and three million years ago. Since that time, the trade winds have transported moisture from the Atlantic to the Pacific, and excessive saltiness of the Atlantic has propelled the conveyor belt.

Support for the scenario I have presented to explain Arctic cooling comes from analogous events at the other end of the world. Early in the age of mammals, about 35 million years ago, climates were very warm at high latitudes on our planet, and then suddenly they cooled. This climatic transition can be traced to events in the vicinity of Antarctica. Then, as now, this continent was centered roughly over the South Pole, but attached to it to form a much larger landmass were South America on the west and Australia on the east. Before the climatic transition, currents from lower latitudes flowed past Antarctica, bathing it in warmth. Then, about 34 million years ago, near the end of the Eocene Epoch (57 million to 34 million years ago), large plates of Earth's upper shell began to move in new ways, breaking South America and Australia away from Antarctica, which was thereby isolated in its polar position. The great counterclockwise currents that cycled through each of the southern oceans—South Atlantic, Indian, and South Pacific—then came to behave like enormous gears, turning another gear in the form of a circular current of water that cycled clockwise around Antarctica. This southern gyre still operates. As happens today, water that became trapped in this gyre must have become increasingly cold as it cycled round and round in its polar location, until its density became so great that it sank to the floor of the deep sea. Then, as now, this cold water spread throughout the deep sea, forming the frigid layer of water at the bottom of the ocean. As this cold gyre formed, it refrigerated Antarctica, triggering the growth of a polar ice cap. Through the transport of its cold waters northward, followed by their upwelling to the surface, the gyre caused climates to cool throughout the world.

This series of events in the south polar region, like the scenario I have described for the north polar region, resulted from movements of Earth's rocky shell. More important, a shared principle lies at the root of each of these reconstructions of a past event of global climatic change: When a sizable body of ocean water becomes largely isolated in a polar region, then that body of water and the atmosphere above it automatically become very cold, and they affect climates throughout the world. (Conversely, a polar region is relatively warm when ocean currents supply it with heat from lower latitudes.) Whereas the isolated body of polar water that formed in the southern hemisphere during the Eocene was a gyre, the one that originated in the northern hemisphere later, during the Pliocene, was a ponded body of water—the uppermost layer of the Arctic Ocean.

The Eocene episode of glaciation and climatic change wrought massive global changes. As oceans cooled, evaporation of their surface waters supplied less moisture to the land; and in the course of several million years, grassy habitats replaced forests in many regions. The result was extinction of many forest-dwelling mammals throughout the world—leaf eaters or animals otherwise dependent on moist, cloistered habitats. The ice age that began later, in the north, caused less extinction of animal life, for two reasons. First, the northern refrigeration system, created by the modern conveyor belt, is weaker than the southern refrigeration system, which is maintained by the current that circles Antarctica. Second, the Antarctic event disrupted a world of remarkably mild, moist climates; the animals adapted to the warmth were these ecologically fragile creatures, ill-fitted to the new, harsher climates. By the time the northern system was set in place, the world had already become what is sometimes dubbed an icehouse world, one that has been pervasively altered by glaciation at one pole. The northern polar system, emplaced more than 30 million years later, simply made things a bit more severe, subjecting many areas at middle and low latitudes to slightly cooler conditions and slightly more pronounced seasonal fluctuations of temperature and precipitation. Of course, Earth's rotational movements have caused climatic conditions to be more severe during glacial maxima of the modern ice age than during glacial minima, such as the one in which we live.

LESSONS FOR THE FUTURE

Might greenhouse warming from our burning of fossil fuels forestall the next glacial maximum? In particular, how might future greenhouse warming affect the conveyor belt, to which I attribute the very existence of the northern ice age? Sad to say, my predictions here are anything but uplifting. Of course, there is debate as to whether greenhouse warming is actually underway. Nonetheless, if we continue to spew carbon dioxide into the atmosphere at an ever-increasing rate, significant global warming will eventually take place—unless northern evergreen forests expand to inhale most of the added carbon dioxide and convert it to plant tissue, or some other as yet unforeseen process compensates for human activities.

Many climatologists predict that if substantial greenhouse warming does occur in the coming centuries, one of the physical casualties may be the oceanic conveyor belt. The idea here is that warmer temperatures in the tropical Atlantic will lead to higher evaporation rates at the ocean surface. This change will enhance an important phenomenon of the present world—the atmospheric transport of moisture to high latitudes, where some of it falls as precipitation. A large increase in precipitation for the northern Atlantic region could dilute the conveyor belt waters to the point where they are no longer dense enough to descend. Thus, the driving force of the conveyor belt would disappear, and along with it, the conveyor belt itself.

Because of heat shed in its direction by the warm waters of the conveyor belt, northern Europe enjoys a remarkably warm climate for its location—the northern half of Germany lies due east of Labrador. It has become conventional in climatological circles to predict that a shutdown of the conveyor belt would plunge Europe into a much colder climate than it experiences today. This view, I argue, is short-sighted. Yes, less heat would be carried northeastward to Europe, but warmer air would flow to Europe from the Arctic. In fact, the entire polar region would heat up considerably—and so, as a consequence, would winters at middle latitudes. This prediction follows from another: Even after future dilution prevents North Atlantic waters from downwelling north of Iceland, a weaker Gulf Stream will remain, driven by wind; failing to sink north of Iceland, the northward flowing waters should continue on into the Arctic Ocean. Even if the inflowing waters become cool enough to sink as they approach the North Pole, they will have transported vast amounts of heat to the Arctic from low latitudes. As these changes get underway, the Arctic Ocean will thaw, and the polar climate will warm. If this chain of events transpires, we will experience global warming on a scale that has not generally been envisioned—we will emerge from the modern ice age.

My apocalyptic scenario is not far-fetched. It parallels one that Knut Aagaard and Lawrence K. Coachman, two experts on Arctic oceanography, advanced as a warning to the Soviet Union in 1975.[2] These American scientists were responding to indications that the Soviets might harness large Siberian rivers, reducing the influx of fresh water to the Arctic Ocean. The surface waters of the Arctic would therefore be left more saline—closer in salt content to typical seawater. Given their increased density, these waters would be more nearly in balance with those of the North Atlantic. Because the North Atlantic waters would not encounter buoyant waters at the brink of the Arctic Ocean, as they do today, the North Atlantic waters would not descend there but would instead flow on into the Arctic, where at some point they would become cold enough to sink. Descent of the Atlantic waters within the Arctic would mix the waters of the polar ocean, eliminating its stratification.

Ironically, relatively warm waters of Atlantic origin flow counterclockwise through the deep Arctic Ocean today. They amount to a subsidiary loop of the conveyor belt, pushing into the polar ocean from the mass of water that descends north of Iceland to drive the conveyor belt. Although warm, this deep water of the Arctic Ocean is quite salty and therefore dense enough to remain below the brackish Arctic pond. Between these two bodies of water and grading into them is an intermediate layer. The lower portion of this intermediate layer is slightly less salty and dense than the loop of conveyor belt water below, so it holds this lower layer in place. The upper portion of the intermediate layer is saltier and denser than the Arctic pond, which therefore floats upon it, so strongly diluted by river water that it can rest on a watery base and so weakly supplied with Atlantic warmth that it remains mostly frozen over.

The layering of today's Arctic Ocean is alarmingly fragile. The intermediate layer that insulates the Arctic pond from the warm Atlantic water below is less than twice as thick as a football field is long, and the Arctic pond itself, which in its frigid isolation refrigerates the entire polar region, is not much deeper than a football field is wide. I believe that if dilution of the upper North Atlantic Ocean allows its warm waters to penetrate deeply into the Arctic before sinking, the modern ice age of the northern hemisphere will come to an end and we will rush headlong back into Pliocene warmth. As temperatures rise around the Arctic Ocean, tundra will give way to evergreen forest, which will further intensify warming by trapping solar heat—a positive feedback. Winters will lose much of their sting, warmer seas will supply more moisture to nearby lands, and forests will invade grassy terrains that receive more rain. More devastating will be the rise of sea level by several feet. Seawater will inundate coastal cities when the Greenland ice cap and other bodies of ice waste away, thereby returning currently immobile water to the ocean.

Of course, we can hope that my scenario will not be tested in the years ahead—that we can manage to avert global warming pronounced enough to push us over the environmental threshold that I have envisioned or across some other, equally disastrous brink that may not yet even come to our attention. Unfortunately, an event of small dimensions on a planetary scale can trigger momentous climatic changes of global proportions. This fact is perhaps the most profound implication of the idea that a spindly little neck of land, by lodging between two great continents, could have set in motion a series of changes in ocean circulation that precipitated the great ice age in which we live.