AGRICULTURAL TERRACES have been constructed for some 2,000 years. Those on the opposite page are in Guizhou Province, China.

HOW DID HUMANS FIRST ALTER GLOBAL CLIMATE?

A bold new hypothesis suggests that our ancestors' farming practices kicked off global warming thousands of years before we started burning coal and driving cars

By William F. Ruddiman

The scientific consensus that human actions first began to have a warming effect on the earth's climate within the past century has become part of the public perception as well. With the advent of coal-burning factories and power plants, industrial societies began releasing carbon dioxide (CO_2) and other greenhouse gases into the air. Later, motor vehicles added to such emissions. In this scenario, those of us who have lived during the industrial era are responsible not only for the gas buildup in the atmosphere but also for at least part of the accompanying global warming trend. Now, though, it seems our ancient agrarian ancestors may have begun adding these gases to the atmosphere many millennia ago, thereby altering the earth's climate long before anyone thought.

New evidence suggests that concentrations of CO_2 started rising about 8,000 years ago, even though natural trends indicate they should have been dropping. Some 3,000 years later the same thing happened to methane, another heat-trapping gas. The consequences of these surprising rises have been profound. Without them, current temperatures in northern parts of North America and Europe would be cooler by three to four degrees Celsius—enough to make agriculture difficult. In addition, an incipient ice age—marked by the appearance of small ice caps—would probably have begun several thousand years ago in parts of northeastern Canada. Instead the earth's climate has remained relatively warm and stable in recent millennia.

GEORG GERSTER Photo Researchers, Inc.

Until a few years ago, these anomalous reversals in greenhouse gas trends and their resulting effects on climate had escaped notice. But after studying the problem for some time, I realized that about 8,000 years ago the gas trends stopped following the pattern that would be predicted from their past long-term behavior, which had been marked by regular cycles. I concluded that human activities tied to farming—primarily agricultural deforestation and crop irrigation—must have added the extra CO_2 and methane to the atmosphere. These activities explained both the reversals in gas trends and the ongoing increases right up to the start of the industrial era. Since then, modern technological innovations have brought about even faster rises in greenhouse gas concentrations.

My claim that human contributions have been altering the earth's climate for millennia is provocative and controversial. Other scientists have reacted to this proposal with the mixture of enthusiasm and skepticism that is typical when novel ideas are put forward, and testing of this hypothesis is now under way.

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The Current View

THIS NEW IDEA builds on decades of advances in understanding long-term climate change. Scientists have known since the 1970s that three predictable variations in the earth's orbit around the sun have exerted the dominant control over long-term global climate for millions of years. As a consequence of these orbital cycles (which operate over 100,000, 41,000 and 22,000 years), the amount of solar radiation reaching various parts of the globe during a given season can differ by more than 10 percent. Over the past three million years, these regular changes in the amount of sunlight reaching the planet's surface have produced a long sequence of ice ages (when great areas of Northern Hemisphere continents were covered with ice) separated by short, warm interglacial periods.

Dozens of these climatic sequences occurred over the millions of years when hominids were slowly evolving toward anatomically modern humans. At the end of the most recent glacial period, the ice sheets that had blanketed northern Europe and North America for the previous 100,000 years shrank and, by 6,000 years ago, had disappeared. Soon after, our ancestors built cities, invented writing and founded religions. Many scientists credit much of the progress of civilization to this naturally warm gap between less favorable glacial intervals, but in my opinion this view is far from the full story.

In recent years, cores of ice drilled in the Antarctic and Greenland ice sheets have provided extremely valuable evidence about the earth's past climate, including changes in the concentrations of the greenhouse gases. A three-kilometer-long ice core retrieved from Vostok Station in Antarctica during the 1990s contained trapped bubbles of ancient air that revealed the composition of the atmosphere (and the gases) at the time the ice layers formed. The Vostok ice confirmed that concentrations of CO_2 and methane rose and fell in a regular pattern during virtually all of the past 400,000 years.

Particularly noteworthy was that these increases and decreases in greenhouse gases occurred at the same intervals as variations in the intensity of solar radiation and the size of the ice sheets. For example, methane concentrations fluctuate mainly at the 22,000-year tempo of an orbital cycle called precession. As the earth spins on its rotation axis, it wobbles like a top, slowly swinging the Northern Hemisphere closer to and then farther from the sun. When this precessional wobble brings the northern continents nearest the sun during the summertime, the atmosphere gets a notable boost of methane from its primary natural source—the decomposition of plant matter in wetlands.

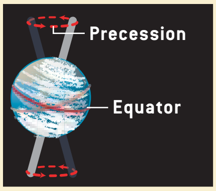
After wetland vegetation flourishes in late summer, it then dies, decays and emits carbon in the form of methane, sometimes called swamp gas. Periods of maximum summertime heating enhance methane production in two primary ways: In southern Asia, the warmth draws additional moisture-laden air in from the Indian Ocean, driving strong tropical monsoons that flood regions that might otherwise stay dry. In far northern Asia and Europe, hot summers thaw boreal wetlands for longer periods of the year. Both processes enable more vegetation to grow, decompose and emit methane every 22,000 years. When the Northern Hemisphere veers farther from

Overview/*Early Global Warming*

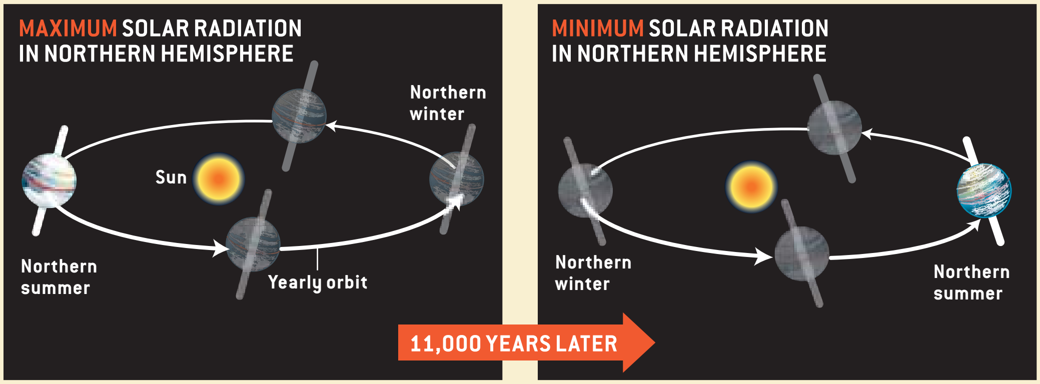
- A new hypothesis challenges the conventional assumption that greenhouse gases released by human activities have perturbed the earth's delicate climate only within the past 200 years.
- New evidence suggests instead that our human ancestors began contributing significant quantities of greenhouse gases to the atmosphere thousands of years earlier by clearing forests and irrigating fields to grow crops.
- As a result, human beings kept the planet notably warmer than it would have been otherwise—and possibly even averted the start of a new ice age.

Orbital Controls over Greenhouse Gases

Natural variations in the earth's orbit, such as those related to precession (*diagrams*), redistribute the sunlight that reaches the globe over long timescales. For the past million years, these subtle changes have driven major dips and swells in atmospheric concentrations of methane and carbon dioxide (*graphs*). Although scientists do not fully understand why, global concentrations of these greenhouse gases respond mainly to changes that occur during summer in the Northern Hemisphere, the time of year when the North Pole is pointed most directly at the sun.

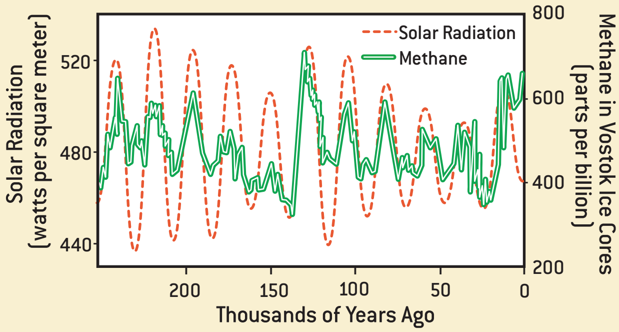


Wobble in the earth's axis of rotation, known as precession, is one of the three orbital cycles that account for sunlight variations in the Northern Hemisphere. Like a toy top about to fall, the earth's axis traces imaginary circles in space, making one revolution every 22,000 years.

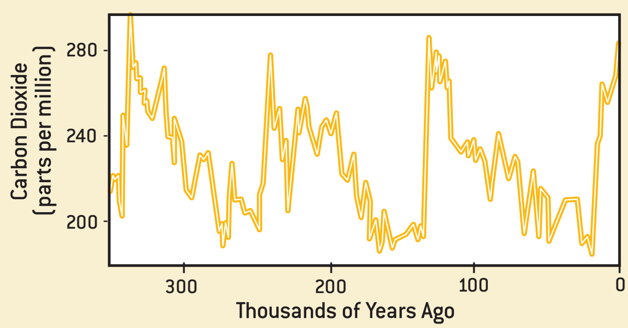


Summer warmth in the Northern Hemisphere peaks once every 22,000 years, when the yearly northern summer coincides with the earth's closest passage to the sun and the Northern Hemisphere receives the most intense sunlight.

Summer heat bottoms out 11,000 years later, after the earth's axis has shifted (precessed) to the opposite position. The Northern Hemisphere then receives the least summer sunlight, because the earth is farthest from the sun.



Methane concentrations rose and fell over the past 250,000 years in near harmony with the precession-induced ups and downs of solar radiation in the Northern Hemisphere. The highest temperatures stimulated extreme methane production in wetlands, which are the atmosphere's primary natural source of this greenhouse gas.



CO_2 concentrations, which fluctuated in cycles over the past 350,000 years, varied in response to precession as well as to shifts in the tilt of the earth's rotational axis and in the shape of its orbit. These other cycles occur every 41,000 and 100,000 years, respectively.

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the sun, methane emissions start to decline. They bottom out 11,000 years later—the point in the cycle when Northern Hemisphere summers receive the least solar radiation.

Unexpected Reversals

EXAMINING RECORDS from the Vostok ice core closely, I spotted something odd about the recent part of the record. Early in previous interglacial intervals, the methane concentration typically reached a peak of almost 700 parts per billion (ppb) as precession brought summer radiation to a maximum. The same thing happened 11,000 years ago, just as the current interglacial period began. Also in agreement with prior cycles, the methane concentration then declined by 100 ppb as summer sunshine subsequently waned. Had the recent trend continued to mimic older interglacial intervals, it would have fallen to a value near 450 ppb during the current minimum in summer heating. Instead the trend reversed direction 5,000 years ago and rose gradually back to almost 700 ppb just before the start of the industrial era. In short, the methane concentration rose when it should have fallen, and it ended up 250 ppb higher than the equivalent point in earlier cycles.

Like methane, CO_2 has behaved unexpectedly over the past several thousand years. Although a complex combination of all three orbital cycles controls CO_2 variations, the trends during previous interglacial intervals were all surprisingly similar to one another. Concentrations peaked at 275 to 300 parts per million (ppm) early in each warm period, even before the last remnants of the great ice sheets finished melting. The CO_2 levels then fell steadily over the next 15,000 years to an average of about

245 ppm. During the current interglacial interval, CO_2 concentrations reached the expected peak around 10,500 years ago and, just as anticipated, began a similar decline. But instead of continuing to drop steadily through modern times, the trend reversed direction 8,000 years ago. By the start of the industrial era, the concentration had risen to 285 ppm—roughly 40 ppm higher than expected from the earlier behavior.

What could explain these unexpected reversals in the natural trends of both methane and CO_2? Other investigators suggested that natural factors in the climate system provided the answer. The methane increase has been ascribed to expansion of wetlands in Arctic regions and the CO_2 rise to natural losses of carbon-rich vegetation on the continents, as well as to changes in the chemistry of the ocean. Yet it struck me that these explanations were doomed to fail for a simple reason. During the four preceding interglaciations, the major factors thought to influence greenhouse gas concentrations in the atmosphere were nearly the same as in recent millennia. The northern ice sheets had melted, northern forests had reoccupied the land uncovered by ice, meltwater from the ice had returned sea level to its high interglacial position, and solar radiation driven by the earth's orbit had increased and then begun to decrease in the same way.

Why, then, would the gas concentrations have fallen during the last four interglaciations yet risen only during the current one? I concluded that something new to the natural workings of the climate system must have been operating during the past several thousand years.

The Human Connection

THE MOST PLAUSIBLE "new factor" operating in the climate system during the present interglaciation is farming. The basic timeline of agricultural innovations is well known. Agriculture originated in the Fertile Crescent region of the eastern Mediterranean around 11,000 years ago, shortly thereafter in northern China, and several thousand years later in the Americas. Through subsequent millennia it spread to other regions and increased in sophistication. By 2,000 years ago, every crop food eaten today was being cultivated somewhere in the world.

Several farming activities generate methane. Rice paddies flooded by irrigation generate methane for the same reason that natural wetlands do—vegetation decomposes in the stagnant standing water. Methane is also released as farmers burn grasslands to attract game and promote growth of berries. In addition, people and their domesticated animals emit methane with feces and belches. All these factors probably contributed to a gradual rise in methane as human populations grew slowly, but only one process seems likely to have accounted for the abruptness of the reversal from a natural methane decline to an unexpected rise around 5,000 years ago—the onset of rice irrigation in southern Asia.

Farmers began flooding lowlands near rivers to grow wet-adapted strains of rice around 5,000 years ago in the south of China. With extensive floodplains lying within easy reach of several large rivers, it makes sense that broad swaths of land could have been flooded soon after the technique was discovered, thus explaining the quick shift in the methane trend. Historical records also indicate a steady expansion in rice irrigation throughout the interval when methane values were rising. By 3,000 years ago the technique had spread south into Indochina and west to the Ganges River Valley in India, further increasing

Human Activities and Greenhouse Gases

Our human ancestors invented agriculture about 11,000 years ago—around the same time that atmospheric concentrations of methane and CO_2 peaked in the wake of the last ice age. Had the gas trends subsequently mimicked older interglacial intervals, as expected, they would have fallen right up through the start of the industrial era. Instead the declining trends of both gases reversed direction several thousand years ago and have risen steadily ever since. The timing of key agricultural innovations—namely, deforestation and rice irrigation—may explain these surprising reversals. *—W.F.R.*

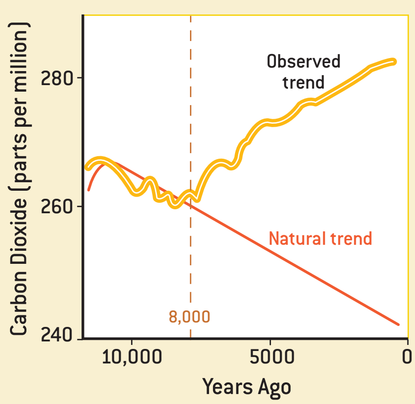
11,000 years ago: Early peoples invent agriculture in Mesopotamia and China

Paleolithic sickle blade

Carbonized wheat

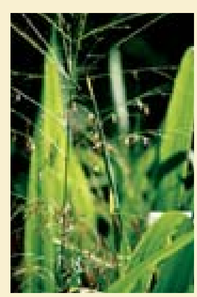
8,000 years ago: Late Stone Age Europeans begin clearing forests to grow wheat, barley, peas and other nonindigenous crop plants

10,000 YEARS AGO | 8,000 YEARS AGO



8,000 years ago: CO_2 trend, which has been falling for 2,500 years, bottoms out and suddenly reverses direction

7,500 years ago: Humans adapt wild rice for cultivation



PETRIE MUSEUM OF EGYPTIAN ARCHAEOLOGY, UNIVERSITY COLLEGE LONDON (*sickle blade* and *carbonized wheat*); JONATHAN BLAIR *Corbis* (*rice*)

THE AUTHOR

WILLIAM F. RUDDIMAN is a marine geologist and professor emeritus of environmental sciences at the University of Virginia. He joined the faculty there in 1991 and served as department chair from 1993 to 1996. Ruddiman first began studying records of climate change in ocean sediments as a graduate student at Columbia University, where he received his doctorate in 1969. He then worked as a senior scientist and oceanographer with the U.S. Naval Oceanographic Office in Maryland and later as a senior research scientist at Columbia's Lamont-Doherty Earth Observatory.

methane emissions. After 2,000 years, farmers began to construct rice paddies on the steep hillsides of Southeast Asia.

Future research may provide quantitative estimates of the amount of land irrigated and methane generated through this 5,000-year interval. Such estimates will be probably be difficult to come by, however, because repeated irrigation of the same areas into modern times has probably disturbed much of the earlier evidence. For now, my case rests mainly on the basic fact that the methane trend went the "wrong way" and that farmers began to irrigate wetlands at just the right time to explain this wrong-way trend.

Another common practice tied to farming—deforestation—provides a plausible explanation for the start of the anomalous CO_2 trend. Growing crops in naturally forested areas requires cutting trees, and farmers began to clear forests for this purpose in Europe and China by 8,000 years ago, initially with axes made of stone and later from bronze and then iron. Whether the fallen trees were burned or left to rot, their carbon would have soon oxidized and ended up in the atmosphere as CO_2.

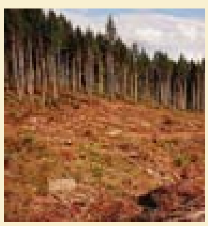
Scientists have precisely dated evidence that Europeans began growing nonindigenous crop plants such as wheat, barley and peas in naturally forested areas just as the CO_2 trend reversed 8,000 years ago. Remains of these plants, initially cultivated in the Near East, first appear in lake sediments in southeastern Europe and then spread to the west and north over the next several thousand years. During this interval, silt and clay began to wash into rivers and lakes from denuded hillsides at increasing rates, further attesting to ongoing forest clearance.

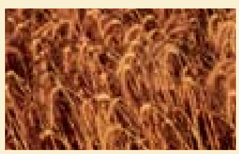
The most unequivocal evidence of early and extensive deforestation lies in a unique historical document—the Domesday Book. This survey of England, ordered by William the Conqueror, reported that 90 percent of the natural forest in lowland, agricultural regions was cleared as of A.D. 1086. The survey also counted 1.5 million people living in England at the time, indicating that an average density of 10 people per square kilometer was sufficient to eliminate the forests. Because the advanced civilizations of the major river valleys of China and India had reached much higher population densities several thousand years prior, many historical ecologists have concluded that these regions were heavily deforested some two or even three thousand years ago. In summary, Europe and southern Asia had been heavily deforested long before the start of the industrial era, and the clearance process was well under way throughout the time of the unusual CO_2 rise.

An Ice Age Prevented?

IF FARMERS WERE responsible for greenhouse gas anomalies this large—250 ppb for methane and 40 ppm for CO_2 by the 1700s—the effect of their practices on the earth's climate would have been substantial. Based on the aver-

5,000 years ago: Farmers in the south of China begin flooding lowlands near rivers to grow rice





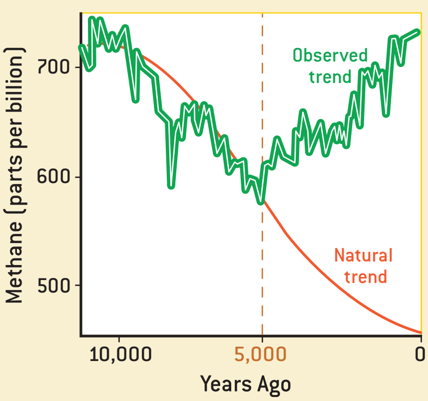
2,000 years ago: Europe, India, Southeast Asia and China have cleared much of their natural forest cover to grow crops such as wheat

200 years ago: Combustion of fossil fuels and accelerating deforestation result in unprecedented releases of greenhouse gases

Otto engine

6,000 YEARS AGO | 4,000 YEARS AGO | 2,000 YEARS AGO | PRESENT

5,000 years ago: Methane trend, which has been falling for 6,000 years, suddenly reverses direction



2,000 years ago: Farmers in Southeast Asia begin to construct terraced rice paddies on steep hillsides

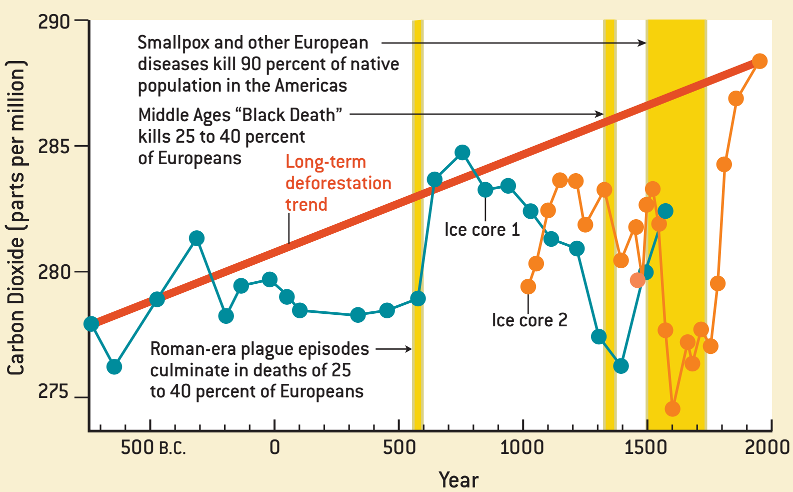
JULIA WATERLOW *Eye Ubiquitous/Corbis* (*irrigation*); THE IMAGE BANK (*deforestation*); VINCE STREANO *Corbis* (*wheat field*); DAVID GREEDY *Getty Images* (*rice terraces*); SCIENCE LIBRARY/SSPL (*combustion engine*); LUCY READING-IKKANDA (*graphs*)

Human Disease and Global Cooling

Concentrations of CO_2 in the atmosphere have been climbing since about 8,000 years ago. During the past two millennia, however, that steady increase at times reversed direction, and the CO_2 levels fell for decades or more. Scientists usually attribute such CO_2 drops—and the accompanying dips in global temperature—to natural reductions in the sun's energy output or to volcanic eruptions. These factors have been regarded as major drivers of climate change over decades or centuries, but for the CO_2 patterns, such explanations fall short—which implies that an additional factor forced CO_2 levels downward. Because I had already concluded that our human ancestors had caused the slow rise in CO_2 for thousands of years by clearing forests for agriculture (*see main article*), this new finding made me wonder whether some kind of reversal of the ongoing clearance could explain the brief CO_2 drops.

The most likely root cause turns out to be disease—the massive human mortality accompanying pandemics. Two severe outbreaks of bubonic plague, the single most devastating killer in human history, correlate well with large CO_2 drops at approximately A.D. 540 and 1350 (*graph*). Plague first erupted during the Roman era, with the most virulent pandemic, the Plague of Justinian, in A.D. 540 to 542. The infamous "Black Death" struck between 1347 and 1352, followed by lesser outbreaks for more than a century. Each of these pandemics killed some 25 to 40 percent of the population of Europe. An even worse catastrophe followed in the Americas after 1492, when Europeans introduced smallpox and a host of other diseases that killed around 50 million people, or about 90 percent of the pre-Columbian population. The American pandemic coincides with the largest CO_2 drop of all, from 1550 to 1800.

Observers at the time noted that the massive mortality rates produced by these pandemics caused widespread abandonment of rural villages and farms, leaving untended farmland to revert to the wild. Ecologists have shown that forests will reoccupy abandoned land in just 50 years. Coupled with estimates of human population and the acreage cultivated by each farmer, calculations of forest regrowth in pandemic-stricken regions indicate that renewed forests could have sequestered enough carbon to reduce concentrations of CO_2 in the atmosphere by the amounts observed. Global climate would have cooled as a result, until each pandemic passed and rebounding populations began cutting and burning forests anew. —*W.F.R.*



MOST DRAMATIC DROPS in atmospheric CO_2 concentrations during the past 2,000 years (as recorded in two Antarctic ice cores) occurred around the same periods that disease outbreaks were taking the greatest toll on human life (*yellow bars*).

age sensitivity shown by a range of climate models, the combined effect from these anomalies would have been an average warming of almost 0.8 degree C just before the industrial era. That amount is larger than the 0.6 degree C warming measured during the past century—implying that the effect of early farming on climate rivals or even exceeds the combined changes registered during the time of rapid industrialization.

How did this dramatic warming effect escape recognition for so long? The main reason is that it was masked by natural climatic changes in the opposite direction. The earth's orbital cycles were driving a simultaneous natural cooling trend, especially at high northern latitudes. The net temperature change was a gradual summer cooling trend lasting until the 1800s.

Had greenhouse gases been allowed to follow their natural tendency to decline, the resulting cooling would have augmented the one being driven by the drop in summer radiation, and this planet would have become considerably cooler than it is now. To explore this possibility, I joined with Stephen J. Vavrus and John E. Kutzbach of the University of Wisconsin–Madison to use a climate model to predict modern-day temperature in the absence of all human-generated greenhouse gases. The model simulates the average state of the earth's climate—including temperature and precipitation—in response to different initial conditions.

For our experiment, we reduced the greenhouse gas levels in the atmosphere to the values they would have reached today without early farming or industrial emissions. The resulting simulation showed that our planet would be almost two degrees C cooler than it is now—a significant difference. In comparison, the global mean temperature at the last glacial maximum 20,000 years ago was only five to six degrees C colder than it is today. In effect, current temperatures would be well on the way toward typical glacial temperatures had it not been for the greenhouse gas contributions from early farming practices and later industrialization.

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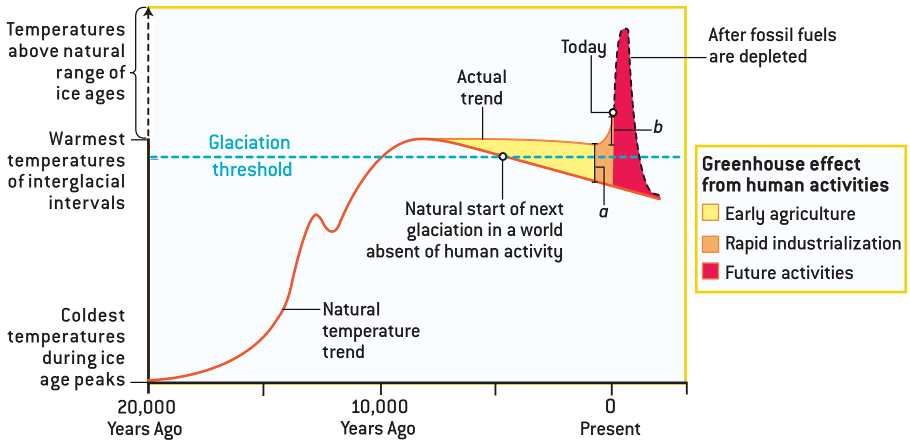

GREENHOUSE EFFECT from human activities has warded off a glaciation that otherwise would have begun about 5,000 years ago. Early human agricultural activities produced enough greenhouse gases to offset most of the natural cooling trend during preindustrial times (*yellow*), warming the planet by an average of almost 0.8 degree Celsius. That early warming effect (*a*) rivals the 0.6 degree Celsius (*b*) warming measured in the past century of rapid industrialization (*orange*). Once most fossil fuels are depleted and the temperature rise caused by greenhouse gases peaks, the earth will cool toward the next glaciation—now thousands of years overdue.

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I had also initially proposed that new ice sheets might have begun to form in the far north if this natural cooling had been allowed to proceed. Other researchers had shown previously that parts of far northeastern Canada might be ice covered today if the world were cooler by just 1.5 to two degrees C—the same amount of cooling that our experiment suggested has been offset by the greenhouse gas anomalies. The later modeling effort with my Wisconsin colleagues showed that snow would now persist into late summer in two areas of northeastern Canada: Baffin Island, just east of the mainland, and Labrador, farther south. Because any snow that survives throughout the summer will accumulate in thicker piles year by year and eventually become glacial ice, these results suggest that a new ice age would have begun in northeast Canada several millennia ago, at least on a small scale.

This conclusion is startlingly different from the traditional view that human civilization blossomed within a period of warmth that nature provided. As I see it, nature would have cooled the earth's climate, but our ancestors kept it warm by discovering agriculture.

Implications for the Future

THE CONCLUSION THAT humans prevented a cooling and arguably stopped the initial stage of a glacial cycle bears directly on a long-running dispute over what global climate has in store for us in the near future. Part of the reason that policymakers had trouble embracing the initial predictions of global warming in the 1980s was that a number of scientists had spent the previous decade telling everyone almost exactly the opposite—that an ice age was on its way. Based on the new confirmation that orbital variations control the growth and decay of ice sheets, some scientists studying these longer-scale changes had reasonably concluded that the next ice age might be only a few hundred or at most a few thousand years away.

In subsequent years, however, investigators found that greenhouse gas concentrations were rising rapidly and that the earth's climate was warming, at least in part because of the gas increases. This evidence convinced most scientists that the relatively near-term future (the next century or two) would be dominated by global warming rather than by global cooling. This revised prediction, based on an improved understanding of the climate system, led some policymakers to discount all forecasts—whether of global warming or an impending ice age—as untrustworthy.

My findings add a new wrinkle to each scenario. If anything, such forecasts of an "impending" ice age were actually understated: new ice sheets should have begun to grow several millennia ago. The ice failed to grow because human-induced global warming actually began far earlier than previously thought—well before the industrial era.

In these kinds of hotly contested topics that touch on public policy, scientific results are often used for opposing ends. Global-warming skeptics could cite my work as evidence that human-generated greenhouse gases played a beneficial role for several thousand years by keeping the earth's climate more hospitable than it would otherwise have been. Others might counter that if so few humans with relatively primitive technologies were able to alter the course of climate so significantly, then we have reason to be concerned about the current rise of greenhouse gases to unparalleled concentrations at unprecedented rates.

The rapid warming of the past century is probably destined to persist for at least 200 years, until the economically accessible fossil fuels become scarce. Once that happens, the earth's climate should begin to cool gradually as the deep ocean slowly absorbs the pulse of excess CO_2 from human activities. Whether global climate will cool enough to produce the long-overdue glaciation or remain warm enough to avoid that fate is impossible to predict. SA

MORE TO EXPLORE

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