

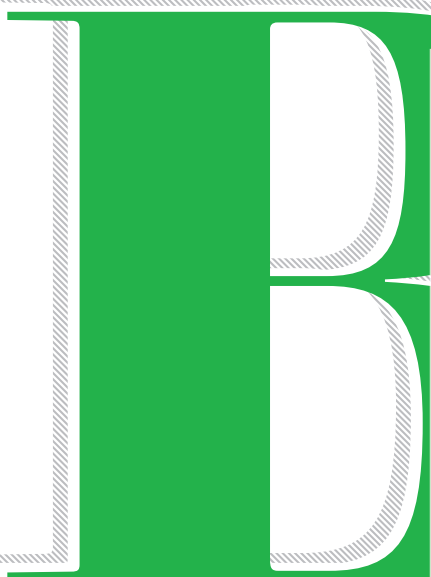
ECOLOGY

# The Great Climate Experiment

How far can we push the planet?

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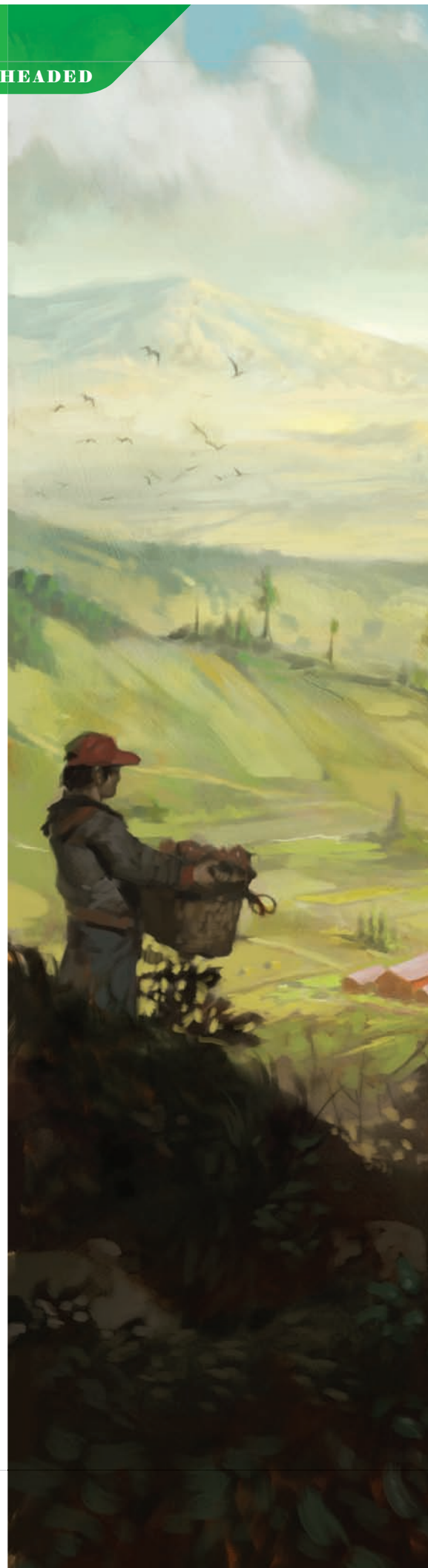


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BUSINESS, GOVERNMENT OR TECHNOLOGY forecasts usually look five or 10 years out, 50 years at most. Among climate scientists, there is some talk of century's end. In reality, carbon dioxide dumped into the atmosphere today will affect Earth hundreds of thousands of years hence.

How will greenhouse gases change the far future? No one can say for sure exactly how Earth will respond, but climate scientists—using mathematical models built from knowledge of past climate systems, as well as the complex web of processes that impact climate and the laws of physics and chemistry—can make predictions about what Earth will look like.

Already we are witnessing the future envisioned by many of these models take shape. As predicted, there has been more warming over land than over the oceans, more at the poles than near the equator, more in winter than in summer and more at night





**NEAR FUTURE:**  
Industrial civilization continues to pump out more and more greenhouse gases with each passing year, which will result in hotter temperatures, an acidified ocean and weirder weather by century's end.





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than in the day. Extreme downpours have become more common. In the Arctic, ice and snow cover less area, and methane-rich permafrost soils are beginning to melt. Weather is getting weirder, with storms fueled by the additional heat.

What are the ultimate limits of the change that we are causing? The best historical example comes from the 100-million-year-old climate of the Cretaceous period, when moist, hot air enveloped dinosaurs' leathery skin, crocodilelike creatures swam in the Arctic and teeming plant life flourished in the CO<sub>2</sub>-rich air. The greenhouse that is forming now will have consequences that last for hundreds of thousands of years or more. But first, it will profoundly affect much of life on the planet—especially us.

#### A DESERT IN ITALY

ONE OF THE GREATEST uncertainties in climate prediction is the amount of CO<sub>2</sub> that will ultimately be released into the atmosphere. In this article, I will assume industrial civilization will continue to do what it has been doing for the past 200 years—namely, burn fossil fuels at an accelerating rate until we can no longer afford to pull them out of the ground.

Just how much CO<sub>2</sub> could we put into the atmosphere? All told, there are about one quadrillion metric tons (10<sup>21</sup> grams) of organic carbon locked up in Earth's sedimentary shell in one form or another. So far we have burned only one twentieth of 1 percent of this carbon, or roughly 2,000 billion metric tons of CO<sub>2</sub>.

With all the carbon locked in Earth's crust, we will never run out of fossil fuels. We are now extracting oil from tar sands and natural gas from water-fractured shale—both resources once thought to be technologically and economically inaccessible. No one can confidently predict just how far ingenuity can take us. Yet eventually the cost of extraction and processing will become so high that fossil fuels will become more expensive than alternative resources. In the scenario envisaged here, we ultimately burn about 1 percent of the available organic carbon over the next few centuries. That is in the range of the amount of extraction most likely to become technologically feasible in the foreseeable future. We further assume that in the future humanity will learn to extract unconventional fossil fuels but will burn them at slower rates.

Without any change in our habits, Earth may warm by about five degrees Celsius (nine degrees Fahrenheit) by 2100, although the actual warming could be half or even double this amount, depending primarily on how clouds respond. This change is about the difference between the average climate of Boston, Mass., and Huntsville, Ala.

In the northern midlatitudes between 30 degrees north and 60 degrees north—a band that includes the U.S., Europe, China, and most of Canada and Russia—the annual average temperature drops two thirds of a degree C with each degree of increasing latitude. With five degrees C of warming in a century, that translates into an average poleward movement of more than 800 kilometers in that period, for an average poleward movement of temperature bands exceeding 20 meters *each day*. Squirrels may be able to keep up with this rate, but oak trees and earthworms have difficulty moving that fast.

Then there will be the rains. Earth is a planetary-scale heat engine. The hot sun warms equatorial air, which then rises and cools. The cooling condenses water vapor in the air, which falls back to Earth as rain—hence, the belt of torrential rains that occur near the equator.

Yet this water condensation also heats the surrounding air, causing it to rise even more rapidly. This hot, dry air reaches as high as jets fly, then spreads laterally toward the poles. At altitude, the hot air radiates heat to space and thus becomes cool, which causes it to sink back toward the planet's surface. The sun's rays pass through this dry, cloudless air, beating down to heat the arid surface. Today such dry air sinks occur at about 30 degrees north and south latitude, thus creating the great belts of desert that encircle the globe.

With greenhouse warming, the rising air is hotter. Thus, it takes more time for this air to cool off and sink back to Earth. As a result, these desert bands move toward the poles.

The climate of the Sahara Desert may move northward. Already southern Europe has been experiencing more intense droughts despite overall increases in precipitation globally, and it may lose the Mediterranean climate that has long been considered one of the most desirable in the world. Future generations may say the same about the Scandinavian climate instead.

Up there in the northern midlatitudes, growing seasons are getting longer. Spring springs sooner: plants flower, lake ice melts and migratory birds return earlier than in the historical past.

That will not be the only benefit to croplands in Canada and Siberia. Plants make food by using the energy in sunlight to merge CO<sub>2</sub> and water. For the most part, plants absorb CO<sub>2</sub> via little pores in leaves known as stomata. When the stomata are open wide, the plants can get plenty of CO<sub>2</sub>, but a lot of water evaporates through these gaping holes. Higher con-

centrations of atmospheric CO<sub>2</sub> mean a plant can get the CO<sub>2</sub> it needs by opening its stomata slightly or even building fewer stomata in leaves. In a high-CO<sub>2</sub> world, plants can grow more using the same amount of water. (This decrease in evaporation from plants also leads to a further decrease in precipitation, and because evaporation causes cooling, the decrease in evaporation causes further warming.)

Such gains will not be felt everywhere. In the tropics, high temperatures already compromise many crops; this heat stress will likely get worse with global warming.

The outlook may be for increased crop productivity overall, with increases in the north exceeding the reductions near the equator. Global warming may not decrease overall food supply, but it may give more to the rich and less to the poor.

### OCEANS OF CHANGE

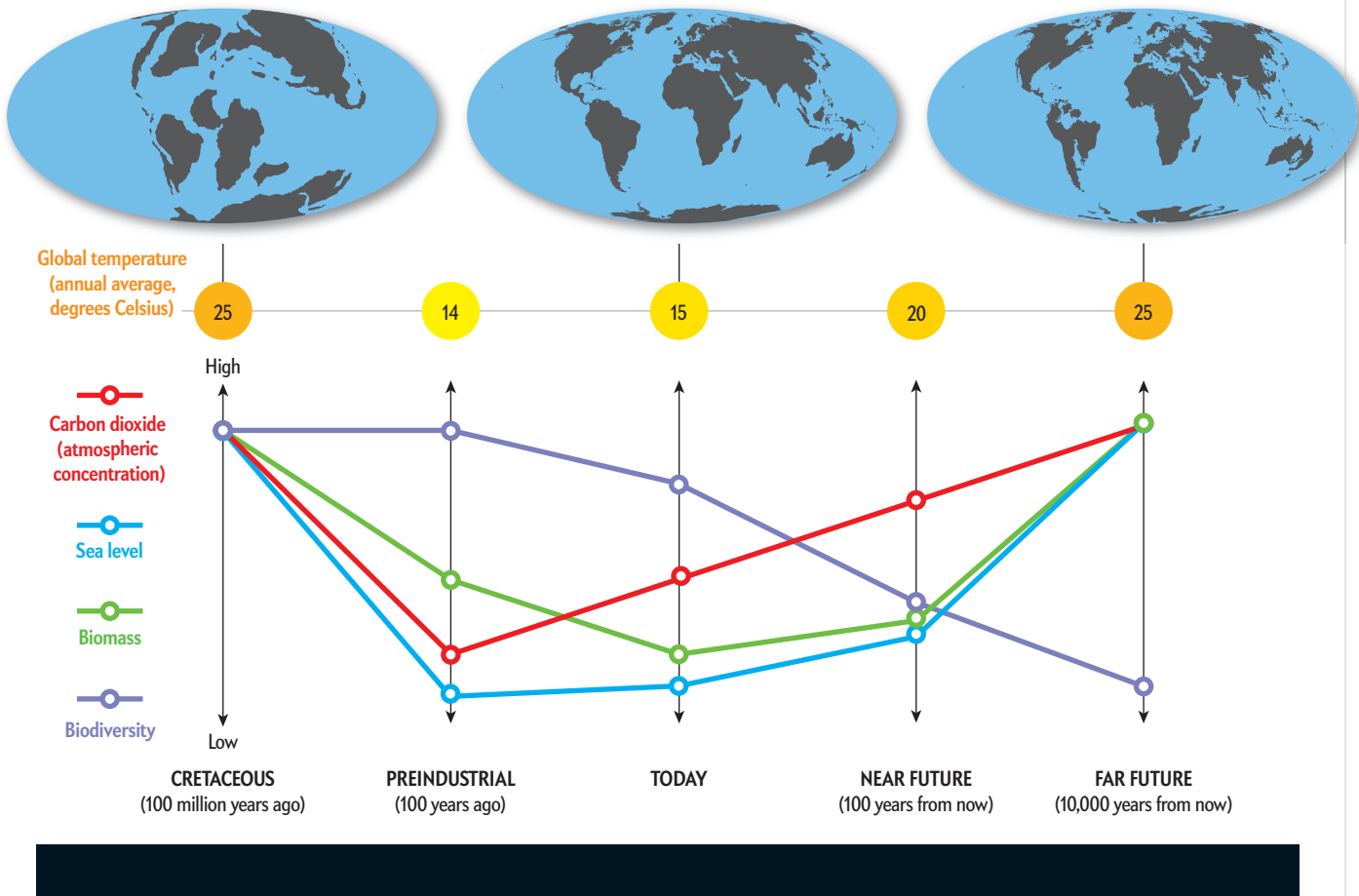
THE VAST OCEANS resist change, but change they will. At no time in Earth's past—with the possible exception of mass-extinction events—has ocean chemistry changed as much and as rapidly as scientists expect it to over the coming decades. When CO<sub>2</sub>

## FAST-FORWARD

# Climate: Past as Future

Assuming we continue to burn fossil fuels at will, releasing greenhouse gases such as carbon dioxide unabated into the atmosphere, the planet will be transformed. Already global temperatures have risen by nearly one degree Celsius—more than twice that in the Arctic. Average temperatures could eventually rise by 10 degrees C, enough to melt the vast quantities of water stored

as ice in the glaciers of Greenland and Antarctica. Enough water could be released to raise sea levels by 120 meters. Atmospheric concentrations of carbon dioxide will reach levels last seen during the Cretaceous period, when dinosaurs roamed Earth, North America was cut in two by an enormous inland sea and crocodilelike creatures inhabited the poles.





**FAR FUTURE:** If greenhouse gas emissions from burning fossil fuels continue unabated, sea levels may rise by 120 meters and polar regions will become much warmer. Any human civilization still extant will need to adapt to these conditions.

enters the oceans, it reacts with seawater to become carbonic acid. In high enough concentrations, this carbonic acid can cause the shells and skeletons of many marine organisms to dissolve—particularly those made of a soluble form of calcium carbonate known as aragonite.

Scientists estimate that more than a quarter of all marine species spend part of their lives in coral reefs. Coral skeletons are made of aragonite. Even if chemical conditions do not deteriorate to the point where shells dissolve, acidification can make it more difficult for these organisms to build them. In just a few decades there will be no place left in the ocean with the kind of chemistry that has supported coral-reef growth in the geologic past. It is not known how many of these coral-dependent species will disappear along with the reefs.

Such chemical changes will most directly affect reef life, but the rest of us would be wise to consider the physical changes afoot. At the most basic level, water acts like mercury in a thermometer: add heat and watch it rise. The sea is also being fed by water now held in ice caps.

In high-CO<sub>2</sub> times in the ancient past, Earth warmed enough for crocodilelike animals to live north of the Arctic Circle. Roughly 100 million years ago annual average polar temperatures reached 14 degrees C, with summertime temperatures exceeding 25 degrees C. Over thousands of years temperatures of this magnitude would be sufficient to melt the great ice sheets of Greenland and Antarctica. With the ice sheets melted completely, sea level will be about 120 meters higher, flooding vast areas. That water's weight on low-

lying continental regions will push those areas down farther into the mantle, causing the waters to lap even higher.

The poles are expected to warm about 2.5 times faster than Earth as a whole. Already the Arctic has warmed faster than anywhere else, by about two degrees C compared with 0.8 degree C globally. At the end of the last ice age, when the climate warmed by about five degrees C over thousands of years, the ice sheets melted at a rate that caused sea level to rise about one meter per century. We hope and expect that ice sheets will not melt more rapidly this time, but we cannot be certain.

### CHASING VENUS

OVER THE PAST several million years Earth's climate has oscillated to cause the waxing and waning of great ice sheets. Our greenhouse gas emissions are hitting this complex system with a hammer. I have presented a scenario in which our climate evolves fairly smoothly, but jumps and starts that could shock biological, social and political systems beyond the limits of their resilience are also possible.

Consider that Arctic warming could cause hundreds of billions of metric tons of methane to rapidly bubble to the atmosphere from Arctic seabeds and soils. Molecule for molecule in the atmosphere, methane is about 37 times better at trapping heat than CO<sub>2</sub>. Were this methane released suddenly, as may have occurred in a warming event 55 million years ago known as the Paleocene-Eocene Thermal Maximum, we could experience truly catastrophic warming. This risk is remote, however, according to most scientists.

Some have also suggested that feedback effects such as melting permafrost could cause a runaway greenhouse scenario where the oceans become so hot they evaporate. Because water vapor is itself a greenhouse gas, such a stronger water cycle could cause Earth to get so hot that atmospheric water vapor would persist and never rain out. In this case, atmospheric CO<sub>2</sub> from volcanoes and other sources would continue to accumulate. Cosmic rays would break apart the water vapor at high altitudes; the resulting hydrogen would eventually escape to space. Earth's climate would then settle into a state reminiscent of its planetary neighbor Venus.

Fortunately, ocean vaporization is not even a remote risk from today's greenhouse gas emissions. Simply put, there is a

limit to how much CO<sub>2</sub> can heat the planet. Once CO<sub>2</sub> and water vapor concentrations rise high enough, the molecules increasingly scatter the incoming sunlight, preventing it from getting any hotter.

If we continue to burn fossil fuels, however, greenhouse gas concentrations in the atmosphere will reach levels last seen in the Cretaceous. Back then, inland seas flooded vast areas of the continents on a hot, moist Earth. Giant reptiles swam in the oceans. On land, dinosaurs grazed on luxuriant plant growth. If we burn just 1 percent of the organic carbon in Earth's crust over the next few centuries, humans will breathe the same CO<sub>2</sub> concentrations as the dinosaurs inhaled and experience similar temperatures.

Compared with the gradual warming of hothouse climates in the past, industrial climate change is occurring in fast-forward. In geologic history, transitions from low- to high-CO<sub>2</sub> atmospheres typically happened at rates of less than 0.00001 degree a year. We are re-creating the world of the dinosaurs 5,000 times faster.

What will thrive in this hothouse? Some organisms, such as rats and cockroaches, are invasive generalists, which can take advantage of disrupted environments. Other organisms, such as corals and many tropical forest species, have evolved to thrive in a narrow range of conditions. Invasive species will likely transform such ecosystems as a result of global warming. Climate change may usher in a world of weeds.

Human civilization is also at risk. Consider the Mayans. Even before Europeans arrived, the Mayan civilization had begun to collapse thanks to relatively minor climate changes. The Mayans had not developed enough resilience to weather small reductions in rainfall. The Mayans are not alone as examples of civilizations that failed to adapt to climate changes.

Crises provoked by climate change are likely to be regional. If the rich get richer and the poor get poorer, could this set in motion mass migrations that challenge political and economic stability? Some of the same countries that are most likely to suffer from the changes wrought by global warming also boast nuclear weapons. Could climate change exacerbate existing tensions and provoke nuclear or other apocalyptic conflict? The social response to climate change could produce bigger problems for humanity than the climate change itself.

### STARTING OVER

THE WOODY PLANTS that flourished during the Cretaceous died, and some became coal over geologic time. The ocean's plankton ended up buried in sediments, and some became oil and gas. The climate cooled as sea life locked CO<sub>2</sub> in shells and skeletons.

The oceans will absorb most of our CO<sub>2</sub> over millennia. The resulting acidification will dissolve carbonate minerals, and the chemical effects of dissolution will allow yet more CO<sub>2</sub> to be absorbed. Nevertheless, atmospheric CO<sub>2</sub> concentrations will remain well above preindustrial levels of 280 parts per million for many tens of thousands of years. As a result, the ebb and flow of ice ages brought on by subtle variations in Earth's orbit will cease, and humanity's greenhouse gas emissions will keep the planet locked in a hothouse.

Over time increased temperatures and precipitation will accelerate the rate at which bedrock and soils dissolve. Streams and rivers will bring these dissolved rocks and minerals, containing elements such as calcium and magnesium, to the oceans. Perhaps hundreds of thousands of years from now some marine organism will take the calcium and CO<sub>2</sub> and form a carbonate shell. That seashell and millions of others may eventually become limestone. Just as the White Cliffs of Dover in England are a remnant of the Cretaceous atmosphere, the majority of carbon in the fossil fuels burned today will become a layer in the rocks—a record, written in stone, of a world changed by a single species. ■

#### MORE TO EXPLORE

**Oceanography: Anthropogenic Carbon and Ocean pH.** Ken Caldeira and Michael E. Wickett in *Nature*, Vol. 425, page 365; September 25, 2003.  
**Climate Change 2007: The Physical Science Basis.** International Panel on Climate Change. Cambridge University Press, 2007. [www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/contents.html](http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html)  
**The Long Thaw.** David Archer. Princeton University Press, 2010.

#### SCIENTIFIC AMERICAN ONLINE

For more on what to expect from climate change, watch the video at [ScientificAmerican.com/sep2012/future-climate](http://ScientificAmerican.com/sep2012/future-climate)