





CLIMATE CHANGE

THE Last Great Global Warming

Surprising new evidence suggests the pace of the earth's most abrupt prehistoric warm-up paled in comparison to what we face today.

The episode has lessons for our future

By Lee R. Kump

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POLAR BEARS DRAW MOST VISITORS TO Spitsbergen, the largest island in Norway's Svalbard archipelago. For me, rocks were the allure. My colleagues and I, all geologists and climate scientists, flew to this remote Arctic island in the summer of 2007

to find definitive evidence of what was then considered the most abrupt global warming episode of all time. Getting to the rocky outcrops that might entomb these clues meant a rugged, two-hour hike from our old bunkhouse in the former coal-mining village of Longyearbyen, so we set out early after a night's rest. As we trudged over slippery pockets of snow and stunted plants, I imagined a time when palm trees, ferns and alligators probably inhabited this area.

Back then, around 56 million years ago, I would have been drenched with sweat rather than fighting off a chill. Research had indicated that in the course of a few thousand years—a mere instant in geologic time—global temperatures rose five degrees Celsius, marking a planetary fever known to scientists as the Paleocene-Eocene Thermal Maximum, or PETM. Climate zones shifted toward the poles, on land and at sea, forcing plants and animals to migrate, adapt or die. Some of the deepest realms of the ocean became acidified and oxygen-starved, killing off many of the organisms living there. It took nearly 200,000 years for the earth's natural buffers to bring the fever down.

The PETM bears some striking resemblances to the human-caused climate change unfolding today. Most notably, the culprit behind it was a massive injection of heat-trapping greenhouse gases into the atmosphere and oceans, comparable in volume to what our persistent burning of fossil fuels could deliver in coming centuries. Knowledge of exactly what went on during the PETM could help us foresee what our future will be like. Until recently, though, open questions about the event have made predictions speculative at best. New answers provide sobering clarity. They suggest the consequences of the planet's last great global

warming paled in comparison to what lies ahead, and they add new support for predictions that humanity will suffer if our course remains unaltered.

GREENHOUSE CONSPIRACY

TODAY INVESTIGATORS think the PETM unfolded something like this: As is true of our current climate crisis, the PETM began, in a sense, with the burning of fossil fuels. At the time the supercontinent Pangaea was in the final stages of breaking

up, and the earth's crust was ripping apart, forming the northeastern Atlantic Ocean. As a result, huge volumes of molten rock and intense heat rose up through the landmass that encompassed Europe and Greenland, baking carbon-rich sediments and perhaps even some coal and oil near the surface. The baking sediments, in turn, released large doses of two strong greenhouse gases, carbon dioxide and methane. Judging by the enormous volume of the eruptions, the volcanoes probably accounted for an initial buildup of greenhouse gases on the order of a few hundred petagrams of carbon, enough to raise global temperature by a couple of degrees. But most analyses, including ours, suggest it took something more to propel the PETM to its hottest point.

A second, more intense warming phase began when the volcano-induced heat set other types of gas release into motion. Natural stirring of the oceans ferried warmth to the cold seabed, where it apparently destabilized vast stores of frozen methane hydrate deposits buried within. As the hydrates thawed, methane gas bubbled up to the surface, adding more carbon into the atmosphere. Methane in the atmosphere traps heat much more effectively than CO₂ does, but it converts quickly to CO₂. Still, as long as the methane release continued, elevated concentrations

IN BRIEF

Global temperature rose five degrees Celsius 56 million years ago in response to a massive injection of greenhouse gases into the atmosphere.

That intense gas release was only 10 percent of the rate at which heat-trapping greenhouse gases are building up in the atmosphere today.

The speed of today's rise is more troubling than the absolute magnitude, because adjusting to rapid climate change is very difficult.

of that gas would have persisted, strongly amplifying the greenhouse effect and the resulting temperature rise.

A cascade of other positive feedbacks probably ensued at the same time as the peak of the hydrate-induced warming, releasing yet more carbon from reservoirs on land. The drying, baking or burning of any material that is (or once was) living emits greenhouse gases. Droughts that would have resulted in many parts of the planet, including the western U.S. and western Europe, most likely exposed forests and peat lands to desiccation and, in some cases, widespread wildfires, releasing even more CO₂ to the atmosphere. Fires smoldering in peat and coal seams, which have been known to last for centuries in modern times, could have kept the discharge going strong.

Thawing permafrost in polar regions probably exacerbated the situation as well. Permanently frozen ground that locks away dead plants for millions of years, permafrost is like frozen hamburger in the freezer. Put that meat on the kitchen counter, and it rots. Likewise, when permafrost defrosts, microbes consume the thawing remains, burping up lots of methane. Scientists worry that methane belches from the thawing Arctic could greatly augment today's fossil-fuel-induced warming. The potential contribution of thawing permafrost during the PETM was even more dramatic. The planet was warmer then, so even before the PETM, Antarctica lacked the ice sheets that cover the frozen land today. But that continent would still have had permafrost—all essentially “left on the counter” to thaw.

When the gas releases began, the oceans absorbed much of the CO₂ (and the methane later converted to CO₂). This natural carbon sequestration helped to offset warming at first. Eventually, though, so much of the gas seeped into the deep ocean that it created a surplus of carbonic acid, a process known as acidification. Moreover, as the deep sea warmed, its oxygen content dwindled (warmer water cannot hold as much of this life-sustaining gas as cold water can). These changes spelled disaster for certain microscopic organisms called foraminifera, which lived on the seafloor and within its sediments. The fossil record reveals their inability to cope: 30 to 50 percent of those species went extinct.

CORE KNOWLEDGE

THAT A SPECTACULAR RELEASE of greenhouse gases fueled the PETM has been clear since 1990, when a pair of California-based re-

searchers first identified the event in a multimillion-year climate record from a sediment core drilled out of the seabed near Antarctica. Less apparent were the details, including exactly how much gas was released, which gas predominated, how long the spewing lasted and what prompted it.

In the years following that discovery, myriad scientists analyzed hundreds of other deep-sea sediment cores to look for answers. As sediments are laid down slowly, layer by layer, they trap minerals—including the skeletal remains of sea life—that retain signatures of the composition of the surrounding oceans or atmosphere as well as life-forms present at the time of deposition. The mix of different forms, or isotopes, of oxygen atoms in the skeletal remains revealed the temperature of the water, for instance.

When well preserved, such cores offer a beautiful record of climate history. But many of those that included the PETM were not in good shape. Parts were missing, and those left behind had been degraded by the passage of time. Seafloor sediment is typically rich in the mineral calcium carbonate, the same chemical compound in antacid tablets. During the PETM, ocean acidification dissolved away much of the carbonate in the sediments in exactly the layers where the most extreme conditions of the PETM era should have been represented.

It is for this reason that my colleagues and I met up in Spitsbergen in 2007 with a group of researchers from England, Norway and the Netherlands, under the auspices of the Worldwide Universities Network. We had reason to believe that rocks from this part of the Arctic, composed almost entirely of mud and clay, could provide a more complete record—and finally resolve some of the unanswered questions about that ancient warming event. Actually we intended to pluck our samples from an eroded plateau, not from underneath the sea. The sediments we sought were settled into an ancient ocean basin, and tectonic forces at play since the PETM had thrust that region up above sea level, where ice age glaciers later sculpted it into Spitsbergen's spectacular range of steep mountains and wide valleys.

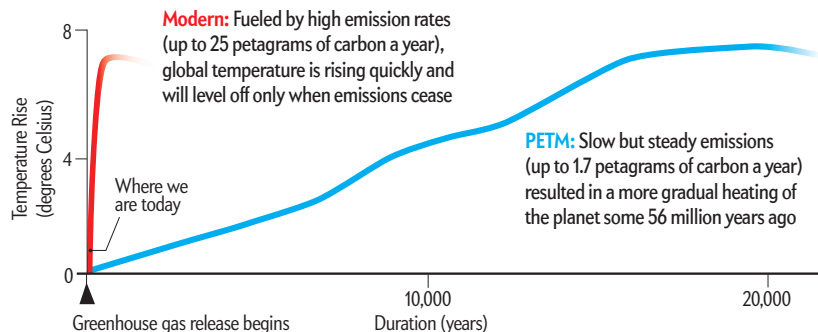
After that first scouting trip from Longyearbyen, while devising plans for fieldwork and rock sampling, we made a discovery that saved much heavy lifting. We learned from a forward-thinking local geologist that a Norwegian mining company he worked for had cored through sediment layers covering the PETM era years earlier. He had taken it on himself to preserve kilometers

SURPRISING FINDING

Now and Then

How fast the world warms depends on how fast greenhouse gases build in the atmosphere. Projections anticipate a warm-up of about eight degrees Celsius by 2400 if fossil-fuel burning and carbon sequestration go unaltered. The projected carbon release, about 5,000 petagrams, is similar in volume to what fueled the Paleocene-Eocene Thermal Maximum, or PETM, but the past rate, once thought to be rapid, was slower than today's.

Global temperature is rising much more quickly today than it did during the PETM



of that core on the off chance that scientists would one day find them useful. He led us to a large metal shed on the outskirts of town where the core is now housed, since cut into 1.5-meter-long cylinders stored in hundreds of flat wood boxes. Our efforts for the rest of that trip, and during a second visit in 2008, were directed at obtaining samples from selected parts of that long core.

Back in the lab, over several years, we extracted from those samples the specific chemical signatures that could tell us about the state of the earth as it passed into and out of the PETM. To understand more about the greenhouse gas content of the air, we studied the changing mix of carbon isotopes, which we gleaned mostly from traces of organic matter preserved in the clay. By making extractions and analyses for more than 200 layers of the core, we could piece together how these factors changed over time. As we suspected, the isotope signature of carbon shifted dramatically in the layers we knew to be about 56 million years old.

STRETCHING TIME

OUR ARCTIC CORES turned out to be quite special. The first to record the full duration of the PETM warm-up and recovery, they provided a much more complete snapshot of the period when greenhouse gases were being released to the atmosphere. We suspected that the unprecedented fidelity of these climate records would ultimately provide the most definitive answers to date about the amount, source and duration of gas release. But to get those results, we had to go beyond extrapolations from the composition and concentration of materials in the cores. We asked Ying Cui, my graduate student at Pennsylvania State University, to run a sophisticated computer model that simulated the warming based on what we knew about the changes in the carbon isotope signatures from the Arctic cores and the degree of dissolution of seafloor carbonate from deep-sea cores.

Cui tried different scenarios, each one taking a month of computer time to play out the full PETM story. Some assumed greater contributions from methane hydrates, for instance; others assumed more from CO₂ sources. The scenario that best fit the physical evidence required the addition of between 3,000 and 10,000 petagrams of carbon into the atmosphere and ocean, more than the volcanoes or methane hydrates could provide; permafrost or peat and coal must have been involved. This estimate falls on the high side of those made previously based on isotope signatures from other cores and computer models. But what surprised us most was that this gas release was spread out over approximately 20,000 years—a time span between twice and 20 times as long as anyone has projected previously. That lengthy duration implies that the rate of injection during the PETM was less than two petagrams a year—a mere fraction of the rate at which the burning of fossil fuels is delivering greenhouse gases into the air today. Indeed, CO₂ concentrations are rising probably 10 times faster now than they did during the PETM.

This new realization has profound implications for the future. The fossil record tells us that the speed of climate change has more impact on how life-forms and ecosystems fare than does the extent of the change. Just as you would prefer a hug from a friend to a punch in the stomach, life responds more favorably to slow changes than to abrupt ones. Such was the case during an extreme shift to a hothouse climate during the Cretaceous period (which ended 65 million years ago, when an asteroid impact killed the dinosaurs). The total magnitude of green-

IMPLICATIONS

Lessons from Past Warmings

Planetary fevers that come on suddenly—such as the scenario unfolding today—are much harder on life than the slower ones are. The fossil record shows that the slow shift to a hothouse from 120 million to 90 million years ago, during the Cretaceous period, was innocuous relative to the PETM, which was 1,000 times more abrupt. The latter episode has long been analyzed for clues to how our own warming trend will play out, but today's much faster temperature change suggests that the consequences for life on earth will be harsher than anything that has come before.



146 Millions of Years Ago (mya)



house warming during the Cretaceous was similar to that of the PETM, but that former episode unfolded over millions, rather than thousands, of years. No notable extinctions occurred; the planet and its inhabitants had plenty of time to adjust.

For years scientists considered the PETM to be the supreme example of the opposite extreme: the fastest climate shift ever known, rivaling the gloomiest projections for the future. In that light, the PETM's outcomes did not seem so bad. Aside from the unlucky foraminifera in the deep sea, all animals and plants apparently survived the heat wave—even if they had to make some serious adaptations to do so. Some organisms shrank. In particular, mammals of the PETM are smaller than both their predecessors and descendants. They evolved this way presumably because smaller bodies are better at dissipating heat than larger ones. Burrowing insects and worms, too, dwarfed.

A great poleward migration saved other creatures. Some even thrived in their expanded territories. At sea, the dinoflagellate *Apectodinium*, usually a denizen of the subtropics, spread to the Arctic Ocean. On land, many animals that had been confined to the tropics made their way into North America and Europe for the first time, including turtles and hoofed mammals. In the case of mammals, this expansion opened up myriad opportunities to evolve and fill new niches, with profound implications for human beings: this grand diversification included the origin of primates.

TOO FAST?

NOW THAT WE KNOW the pace of the PETM was moderate at worst and not really so fast, those who have invoked its rather innocuous biological consequences to justify impenitence about fossil-fuel combustion need to think again. By comparison, the

Cretaceous Hothouse (Slow)

Rate of heating: 0.000025 degree Celsius per 100 years

Duration: Millions of years

Overall warming: 5 °C

Main underlying cause: Volcanic eruptions

Environmental change: Oceans absorbed carbon dioxide slowly so did not acidify

Life's response: Nearly all creatures had time to adapt or migrate



65 mya

PETM (Moderately fast)

Rate of heating: 0.025 °C per 100 years

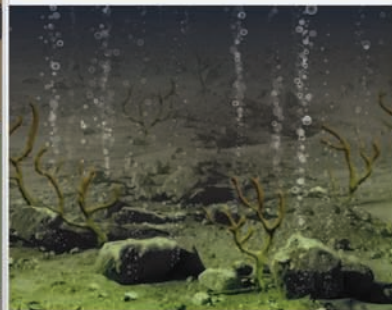
Duration: Thousands of years

Overall warming: 5 °C

Main underlying cause: Volcanoes; methane bubbling up from the ocean bottom; peat and coal fires; thawing permafrost

Environmental change: The deep sea acidified

Life's response: Some seafloor life went extinct, but most life on land adapted or migrated



56 mya

34 mya

Modern Warming (Fast)

Rate of heating: 1 to 4 °C per 100 years

Duration: Decades to hundreds of years

Overall warming: 2 to 10 °C, projected over the next 200 to 300 years

Main underlying cause: Fossil-fuel burning

Environmental change: Acidifying oceans; more extreme weather; glacier melting; sea-level rise

Life's response: Poleward movement of many species; habitat loss; coral bleaching; extinctions



C E O U S

PALEOCENE

E O C E N E

Today ►

climate shift currently under way is happening at breakneck speed. In a matter of decades, deforestation and the cars and coal-fired power plants of the industrial revolution have increased CO₂ by more than 30 percent, and we are now pumping nine petagrams of carbon into the atmosphere every year. Projections that account for population growth and increased industrialization of developing nations indicate that rate may reach 25 petagrams a year before all fossil-fuel reserves are exhausted.

Scientists and policy makers grappling with the potential effects of climate change usually focus on end products: How much ice will melt? How high will sea level rise? The new lesson from PETM research is that they should also ask: How fast will these changes occur? And will the earth's inhabitants have time to adjust? If change occurs too fast or if barriers to migration or adaptation loom large, life loses: animals and plants go extinct, and the complexion of the world is changed for millennia.

Because we are in the early interval of the current planetary fever, it is difficult to predict what lies ahead. But already we know a few things. As summarized in recent reports from the Intergovernmental Panel on Climate Change, ecosystems have been responding sensitively to the warming. There is clear evidence of surface-water acidification and resulting stress on sea life [see "Threatening Ocean Life from the Inside Out," by Marah J. Hardt and Carl Safina; *SCIENTIFIC AMERICAN*, August 2010]. Species extinctions are on the rise, and shifting climate zones have already put surviving plants and animals on the move, often with the disease-bearing pests and other invasive species winning out in their new territories. Unlike those of the PETM, modern plants and animals now have roads, railways, dams, cit-

ies and towns blocking their migratory paths to more suitable climate. These days most large animals are already penned into tiny areas by surrounding habitat loss; their chances of moving to new latitudes to survive will in many cases be nil.

Furthermore, glaciers and ice sheets are melting and driving sea-level rise; coral reefs are increasingly subject to disease and heat stress; and episodes of drought and flooding are becoming more common. Indeed, shifts in rainfall patterns and rising shorelines as polar ice melts may contribute to mass human migrations on a scale never before seen. Some have already begun [see "Casualties of Climate Change," by Alex de Sherbinin, Koko Warner and Charles Ehrhart; *SCIENTIFIC AMERICAN*, January].

Current global warming is on a path to vastly exceed the PETM, but it may not be too late to avoid the calamity that awaits us. To do so requires immediate action by all the nations of the world to reduce the buildup of atmospheric carbon dioxide—and to ensure that the Paleocene-Eocene Thermal Maximum remains the last great global warming. ■

MORE TO EXPLORE

The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future. Francesca A. McInerney and Scott L. Wing in *Annual Review of Earth and Planetary Sciences*, Vol. 39, pages 489–516; May 2011.

America's Climate Choices. Committee on America's Climate Choices, National Research Council of the National Academies. The National Academies Press, 2011.

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SCIENTIFIC AMERICAN ONLINE

See a slide show of the author and his collaborators in the field at ScientificAmerican.com/jul2011/climate-change