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HOT BODIES

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ON PLANET B, IT RAINS GLASS

The wildest climates in the universe



The Climates Issue

TALES OF WONDER AND TURMOIL

ISSUE 63

Science Connected

NAUTILUS



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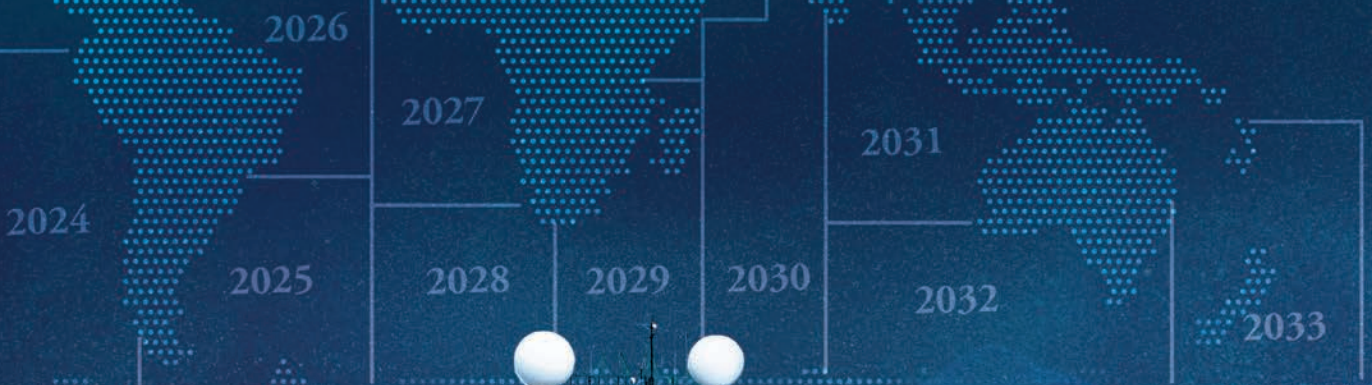




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CONTACT

360 W 36th Street, 7S
New York, NY 10018
info@nautil.us

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The Climates Issue

BY KATHERINE HARMON COURAGE

W

HEN WE SET OUT to make our Climates Issue, we planned to make it wild and expansive. Any way you could think to interpret the word *climate*, you might just find a story on it. But as the stories and the conversations circled, they inevitably coalesced around The Big One, the one with the weightiest center of gravity right now: planetary climates.

The one we're on, of course, is careening at an accelerating velocity toward something radically different than it's been for quite a long time. (Tens of millions of years.) We may think we know enough, have heard enough. But, on a deeper look, the mysteries blossom forth.

On a glacier on the side of Washington's Mount Rainier, as the summer sun sets, animals called ice worms inch through the snow and ice to emerge by the *billions*. Scientists still don't know why they come out only under the cover of night or how they survive in the glacier, as they don't seem to be able to tolerate freezing temperatures. Paradise Glacier, their home, once held a vast system of ice caves, a favorite destination of tourists and hikers a century ago, even into the 1980s. Now the glacier is greatly reduced, of course—about 12 percent of its first-mapped size—and its ice caves vanished. But it is still full of intrigue. We just had to look closer. When researchers recently took a bit of its ice and melted it down, they found genetic traces from every domain of life and four different kingdoms. In glacial ice! We still don't know what's there, right here, in one of the best-studied glaciers in the lower 48, as science journalist Sofia Quaglia uncovers in this issue.

You might also not yet know about the olm. That's probably because even second-generation olm scientists are still trying to figure it out. These sizable salamanders—which look quite a lot like elongated, eyeless axolotls—live in karst caves, a thousand feet below ground. If that didn't make them hard enough to study, they are also incredibly sensitive to light and vibration and even to electromagnetic fields emitted by scientific equipment. Writer Gary Hartley takes us along on a reporting trip to a specialized cave lab in Slovenia where one husband-and-wife team is hatching an elaborate plan for a new AI approach to study these canaries in the deep-climate coal mine.

The issue gets wilder still. Astrophysicist Sean Raymond explains how erratic orbits of *other* planets might super-prime their climates for life; and decorated climate scientist and author Kate Marvel reveals what, after all, Poseidon has been trying to tell us. We also journey inside our cells to find out how heatwaves are changing our own DNA.

Yes, there may be plenty to be weary about in pondering the world's various climates right now (for that, one writer teaches us about a helpful German word, used by Goethe: *Weltschmerz*, which translates as “world-pain”). But, hey, at least we're not on planet HD 189733 b. There, the winds howl at 5,400 miles per hour driving a hard rain of molten silicates, essentially liquid glass. So for now, we can marvel at the wonders of the climates we have right here in front of us.

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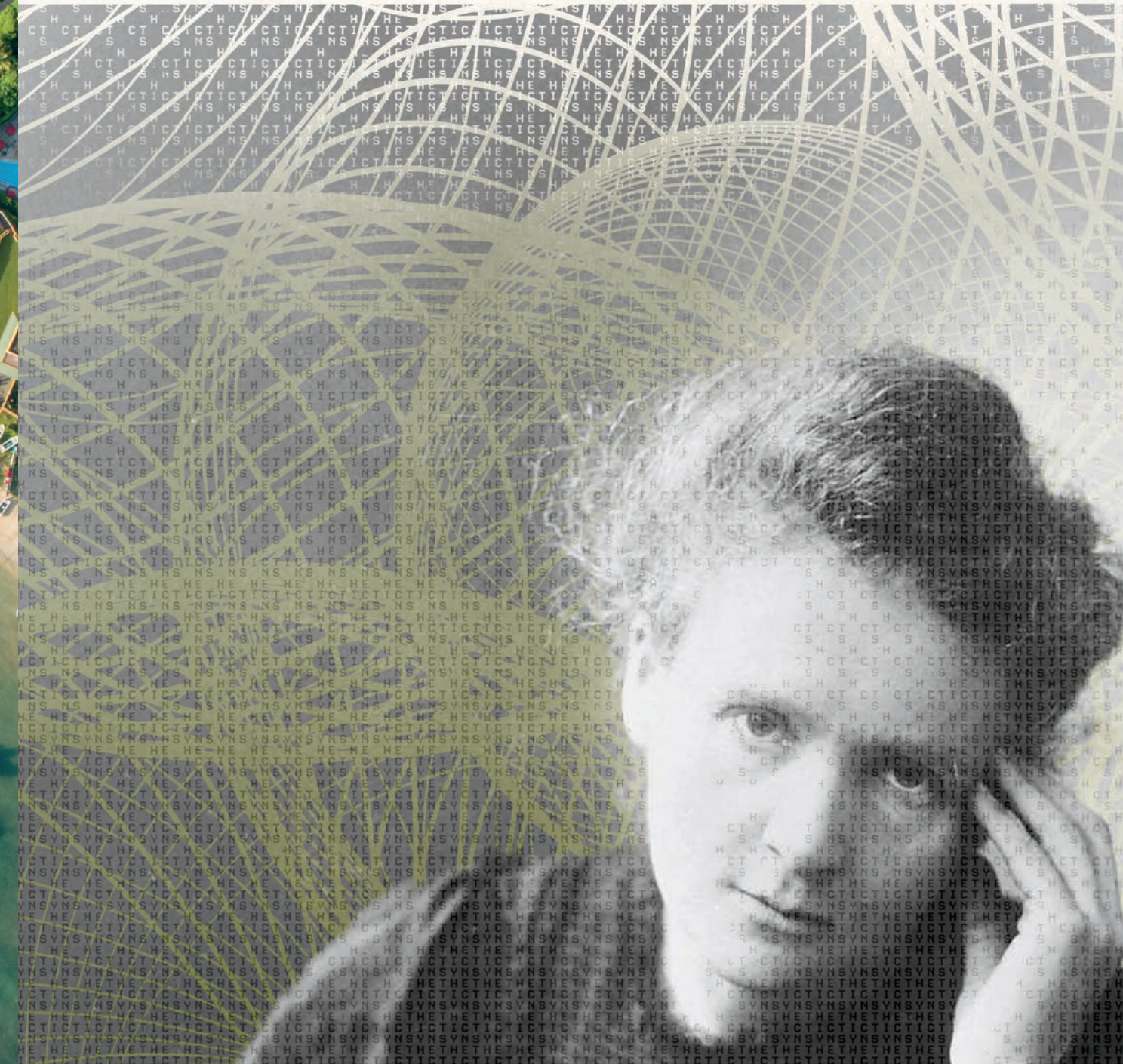
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Natural Intelligence: *High Complexity, Low Energy, Infinite Imagination*

Marie Skłodowska-Curie (1867–1934) was a Polish-born physicist and chemist who became the first woman to win a Nobel Prize and the only person to win in two different sciences — Physics (1903, for research on radioactivity) and Chemistry (1911, for discovering radium and polonium). She pioneered the study of radioactivity — a term she coined — developed methods for isolating radioactive isotopes, and applied her research to medicine, including early cancer treatments. Curie was also the first female professor at the University of Paris. Her groundbreaking work laid the foundation for nuclear physics and radiotherapy.





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THE PORTHOLE

Short sharp looks at science

GEOSCIENCE

The Oldest Rock on Earth

WHEN GEOLOGIST HANIKA RIZO goes into the field she spends most of her time looking at her feet. Simply by trekking across the stark Arctic landscape in Northern Quebec, and paying close attention to the ground, she can glean clues about deep time in the color, texture, and arrangement of the solid outcrops of ancient rock that lie exposed here. Large, bauble-like shapes in the magma—"pillow lava"—speak of contact with water. Finding vestiges of water is always exciting, Rizo says, given that it is one of the requirements for the evolution of life. But the ultimate prize lies in the search for Earth's oldest rock, which can serve as a window into the embryonic stages of Earth's formation.

In a publication this summer, together with colleagues, Rizo, a scientist at Carleton University in Ottawa, described rocks at one study site, the Nuvvuagittuq Greenstone Belt, as dating to 4.16 billion years ago, making them some of the oldest rocks ever collected on Earth, possibly the oldest ever to have formed on the planet.

"The chemistry of the rocks tells us that they look very similar to the oceanic crust today," Rizo says. Their surface is hard and crystalline, made of basalt. Rizo calls them the "first rocks" or the "oldest rocks" interchangeably. Geologists believe that to qualify as a "rock," a piece of the Earth must be taken from the crust, which first formed once our planet's mantle stabilized, the



upper layer of hot, churned-up magma cooling into a shell on which continents and oceans rest.

On a geological time scale the formation of the first or the oldest rock marks the end of the so-called Hadean period, Rizo says. At the moment, this boundary is set by rocks found at the Acasta Gneiss Complex in Yellowknife, Canada, which date to 4.05 billion years ago. But the new rocks are clearly older than that, Rizo says. The finding pushes the timeline for the formation of Earth's first crust back by 130 million years. It also accelerates the timeframe for how quickly life may have emerged after the Earth formed, which Rizo hopes to study next in collaboration with paleobiologists who will look for microfossils of cells in the area.

"The goal is to see if [we] can find traces of life in those rocks. If they are confirmed, then it would mean that life actually began very early on, when these rocks were formed," Rizo says.

The Nuvvuagittuq Greenstone Belt is a chunk of a craton—the durable cores of the modern continents. The Inuit of Inukjuak, on whose homeland the site falls, describe the landscape as dating to "time immemorial,"



an era that stretches beyond living memory, oral tradition, and recorded history, going back to the beginning of existence.

When Rizo and her colleagues travel to Nuvvuagittuq, they require permission to work on the land and rely on local chaperones to help navigate the landscape. The Nuvvuagittuq Greenstone Belt is flat and treeless, so the Inuit use Inukshuk landmarks to help with navigation. These Inukshuks are sculptures made of stone—a sophisticated and enduring form of communication, navigation, and cultural expression that has been integral to survival in one of the world's most challenging environments.

To collect samples of rock, Rizo uses a small hammer she carries in her backpack. “We collect just what we need,” she says, rocks that are no larger than the size of “a grapefruit.” Once she is back in the lab, the rocks are cleaned of lichen, and the exterior part is removed to get to the core, “the most preserved piece of the rock,” Rizo says. The heart of the rock is crushed and dissolved in powerful acids. When all the elements are in solution Rizo can look for relationships between them that predict their age.

The consensus among geologists is that parts of the Nuvvuagittuq Greenstone Belt are at least 3.7 billion years old, but findings of even older rocks have proliferated since 2008, when the age of a rock from the region was estimated to be 4.28 billion years. That research was led by Rizo's husband, Jonathan O'Neil. The pair have worked together for more than a decade and are co-authors of the most recent study that arrived at the 4.16-billion-year date.

But some scholars remain skeptical. They were never convinced by O'Neil's startling findings from 2008 and have similar doubts about the new finding. The gold standard for aging rocks is to look at zirconium crystals, which contain traces of radioactive uranium, whose decay sets the rhythm for measuring time. But the rocks that Rizo and O'Neil work with contain no zirconium. Out of necessity, they chose the rare Earth element neodymium, instead, which is traditionally used to age asteroids. “If you have a zircon age, no one's going to dispute it,” Rizo says, but other techniques leave room for doubt.

“It's plausible” says Jörg Elis Hoffmann, a geologist from the University of Berlin, who specializes in ancient

The finding accelerates the timeframe for how quickly life may have emerged after the Earth formed.

rocks, and who was not involved in the studies at the Nuvvuagittuq Greenstone Belt. Hoffmann is especially convinced by the latest analysis. There were two separate methods used to age the rocks, and they both arrived at the same age estimate, Hoffman says. “The data is coherent,” he says. But there is a snag. A separate study concerned with subduction processes published earlier this year suggests that rocks at the Nuvvuagittuq Greenstone Belt could have been fused with pieces of ancient mantle that is 4.4 billion years old. This could have scrambled the age signature.

While much scientific progress is driven by debate and the reinterpretation of data, in this case, “the problem is, with these rocks, no other group can take any samples there anymore,” Hoffmann says. Hoffmann believes that what is missing here, crucially, is the work of being at the field site together, on foot, gathering the observational data that goes along with lab analyses. “When people have different opinions, the best is actually to go together in the field,” Hoffmann says. The context on the ground is invaluable, Rizo agrees.

But shortly after the COVID-19 pandemic subsided and borders re-opened, the Inuit closed off their land to all scientific expeditions. Some visiting scientists had vandalized Inukshuks, Rizo says, while other groups extracted whole slabs of the landscape for purported museum curations. The Inuit decided the unethical behavior had to stop. “They have been there for longer than we have ever had, and I totally understand that they decided to close access,” Rizo says.

The resolution to the scientific debate may have to wait, but Rizo is hopeful about patching local relationships.

—Elena Kazamia



MICROBIOLOGY

These “Junk” Proteins May Fuel Adaptation

CELL BIOLOGIST AMY GLADFELTER recently set out to solve a riddle that concerns one of the most fundamental features of evolution: adaptation. After a decade of study, she

had noticed that one of her favorite fungi, *Ashbya gossypii*, thrives in a wide variety of environments, from the tropics of Trinidad to the often frigid plains of Wisconsin. How, she began to wonder, did the simple filamentous fungus, with its tiny genome and simple life cycle, evolve such versatility—and how did the beach-town strains differ from the cold-adapted ones?

Gladfelter decided to tinker with *Ashbya gossypii*'s genetic code to see what she could find out. In her laboratory at Duke University School of Medicine, she and her team sifted through 70 strains of the fungus and started methodically swapping proteins in its DNA. In particular, they focused on a protein called Whi3, famous for being a little unpredictable. Instead of locking into a specific position inside a cell or maintaining a single three-dimensional shape, like most proteins, Whi3 is messier and more chaotic: It migrates from one part of the cell to another depending on cellular conditions, and its amino acid sequences are unstable, tending to feature repeats and substitutions.

Gladfelter's team took one fungi strain from Wisconsin that typically grows at a cool 50 degrees Fahrenheit, and another strain from Florida that is accustomed to sweltering 99-degree heat, and swapped small sections of their Whi3 proteins. The researchers discovered that these simple alterations were enough to make the cold-adapted fungus behave like its beach-loving sibling. Whereas the Wisconsin fungus would have typically stopped growing and died if it had been transplanted to Florida, cells that had bits of the Whi3

from the Florida-living strain grew and branched out instead, stretching filaments across petri dishes kept at a balmy 98.6 degrees Fahrenheit. Something about Whi3 had helped the organism learn to take the heat.



“We saw, wow, that was sufficient to make the cold fungus behave essentially like it had come from a warm climate,” says Gladfelter.

The new hybrid was now more sensitive to the cold, too, picking up both the strengths and the weaknesses of its warmer counterpart. Something similar happened when they gave the Florida strains bits of the Whi3 protein from the Wisconsin fungus; the Florida strains became more Wisconsin-like—more cold-tolerant and more heat-sensitive.

The findings add to a growing body of research that suggests that a class of funky proteins known as disordered proteins, found inside fungi and plants—but also in animals, including humans—play a key role in helping the Earth's creatures adapt to their surroundings and acclimate to different environments.



Scientists believe that learning more about these proteins might help them better engineer heat-resistant plants that could tolerate climate change—and even to understand the very nature of adaptation itself.

“We know these proteins are common, we know they’re ubiquitous,” says Gladfelter, but scientists don’t yet know exactly how and why—and what these proteins are doing, on a molecular level, that’s so special. “There’s probably a lot of different ways these [disordered] proteins can change to make fungi more or less temperature sensitive, right? But we don’t know yet what those rules are, and really what the grammar is for that.”

She thinks the powers of disordered proteins they’ve found so far are just the start: “We’ll see whether we’re right.”

FUNCTION GENERALLY FOLLOWS FORM in the world of proteins. They are built of amino acid chains, which can crinkle and bend into a variety of origami-like shapes—some are like globs, others are like strings, for example. The chemistry-textbook dogma has always been that a protein’s purpose is determined by its structure: how it folds.

That is, until scientists first encountered disordered proteins and noticed that their amino acid sequences could shapeshift. In some of the disordered proteins, they found, all of the amino acids could switch places. In others, just one arm of the protein was fluid.

“This guy in my lab, he showed me this funny protein,” says Vladimir Uversky, now a protein expert at the University of Florida, who found his first disordered proteins while working in Russia in 1993. Initially, Uversky dismissed these proteins as one-off flukes or examples of nature gone awry. Maybe something was wrong in his experimental setup, and this was junk of the cell, Uversky thought. But then he realized it wasn’t an exception—it was a new rule.

“I got extremely excited about this idea,” Uversky recalls. At the turn of the century, he published his first paper describing a new category of proteins with intrinsically disordered sequences and no structure, which are extremely important for biology, nonetheless. We actually have two different protein universes, Uversky decided. “One universe of structure, another universe of disorder,” he says. “People were telling me that I was crazy.”

We actually have two different protein universes.

As computational models got better, though, it got easier for Uversky to identify more of these chaotic proteins and to gather evidence to support his case. The new findings suggest that half of all proteins made by living things are disordered—either fully or partially—and that disordered proteins are involved in crucial functions like DNA transcription, cell division, and immunity, among others. These messy molecules cropped up in studies on humans, plants, and fungi. Other research revealed that the more complex the organism, the more likely it is to have disordered proteins.

Uversky argues that disordered proteins were probably the first proteins to evolve, and the structured proteins we know today came later. He believes that disordered proteins play a central role in the adaptability of organisms, and speculates that this may have been especially so many thousands of years ago, when the environment was much harsher and hotter than today.

Uversky believes Gladfelter’s work on the different cold and hot strains of *Ashbya gossypii* supports these speculations, and the larger idea that, “Disorder is crucial for adaptability.”

DISORDER CERTAINLY SEEMS TO BE potent. In the *Ashbya gossypii* study, Gladfelter’s team swapped only 20 of the messy amino acids from the over 720 amino acids in the Whi3 protein—and that was enough for her fungus from Wisconsin to start acting like a fungus from Florida. Just a small segment of disordered protein can radically change the environment inside the cell, Gladfelter says.

She notes that, basically, the amino acid sequences in these whacky proteins are flexible enough that they can shift in response to the environment, allowing species that have them to adapt quickly. These shifts “may manifest during an organism’s lifetime,” she says, and if they are adaptive, “they get fixed in a population over multiple generations.”



Gladfelter's findings are supported by research from another team of scientists, who recently analyzed the influence that disordered parts of a protein called ELF3 (a shorthand for early flowering) have on the temperature sensitivities of thale cress plants. These sequences seem to act as temperature-sensing dimmer switches. In plants that have this disordered bit, ELF3 switches off when temperatures reach around 81 degrees Fahrenheit, enabling the thale cress to grow more quickly. When this disordered region is absent, the ELF3 does not switch off, and the plant continues growing slowly like a plant in a cool climate, even when temperatures rise.

Study author Philip Wigge, a professor of plant adaptation from the Leibniz Institute of Vegetable and Ornamental Crops in Germany, suggests thinking of the disordered proteins like sails on a boat. If it's relatively calm, one wants the largest possible sail to catch what little wind is blowing. When it's very windy, however, smaller sails are needed or the boat will catch too much wind and tip into the sea. In the same way, ELF3 proteins in plants from cooler climates have very large disordered segments to sense small amounts of heat, allowing for brief periods of supercharged growth,

while plants from tropical climates have smaller disordered parts. They don't need the extra boost in growth during warm periods since there is plenty of heat to go around. In a forthcoming paper, Wigge suggests disordered proteins serve the same function in mosses, too. "This is a very broadly conserved mechanism," he says.

A study published last year compared three closely related types of yeasts and yielded similar results; studies on rice and soybeans, too. Even studies on tardigrades, the super hardy micro-animals known for surviving the extreme conditions of outer space, suggest they are so great at avoiding death by desiccation and extreme temperatures due to an abundance of intrinsically disordered proteins.

Outside of the laboratory, these proteins might play a crucial role in allowing certain plants and fungi to persist in their native ecosystems as the Earth's climate shifts. These same proteins could likely be used to adapt certain crops to climate change conditions via genetic engineering, says Wigge—introducing more disorder in plants that need more flexibility. While the work is still preliminary, says Wigge, "the race is now on."

—Sofia Quaglia

PALEONTOLOGY

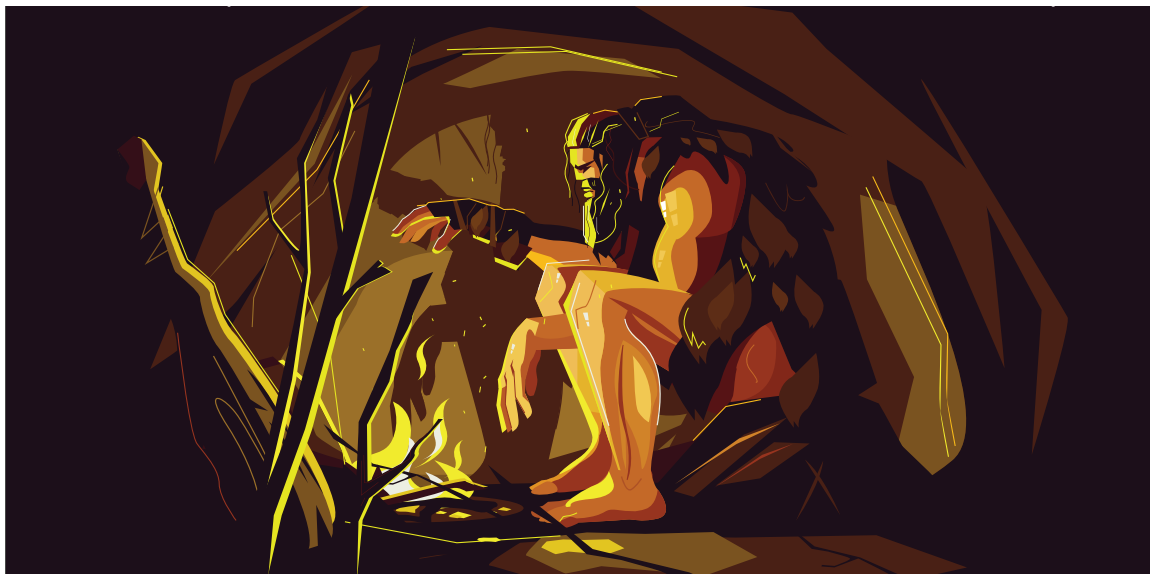
We Didn't Start the Fire

FEW SKILLS PLAY a more elemental role in the story of humanity's progress from hunter-gatherer to civilization builder than the mastery of fire. These blazes provided not just warmth and protection against predators, but also a draw for social gatherings, a means of cooking food, a source of light, and a method to forge new tools. Human use of fire eventually became so sweeping that it re-shaped Earth's ecosystems and began to influence the planet's climate.

Archaeological remnants suggest human ancestors first began to use fire in a controlled manner around 400,000 years ago, but chronological gaps in the record have made it difficult to determine when their mastery of the conflagration became widespread enough

to impact the Earth itself. Some scientists suspected this happened relatively recently, around 11,000 years ago, during the Holocene, when agriculture had already taken root. Now a team of researchers from China, Germany, and France has found evidence in carbon cores that humans came to use fire extensively around 50,000 years ago, during *Homo sapiens'* first successful migration out of Africa to Europe, Asia, Southeast Asia, and Australia. This period coincided with rising population densities and cold glacial conditions. The researchers published their findings in PNAS.

The team of scientists, from the Institute of Oceanology of the Chinese Academy of Sciences, together with collaborators from other institutions in China and Europe, analyzed carbon in three 300,000-year-old



sediment cores taken from the East China Sea. Around 50,000 years ago, the cores showed a doubling in pyrogenic carbon, which persisted over time. Pyrogenic carbon, or charred plant remains, is created when vegetation burns but is not completely consumed by fire. Similar observations have been made in pyrogenic carbon records from the Sulu Sea in the Philippines, the Caroline Basin north of Papua New Guinea, and north-eastern Australia.

Taken together, these findings suggest human fire use spread rapidly across the globe and permanently altered the Earth's carbon cycle well before the last

glacial maximum, when vast ice sheets covered portions of North America, Europe, and Asia, according to the team of researchers. Before they had even settled down to work the land and raise crops, our ancestors had likely begun to alter their home planet, increasing carbon dioxide in the atmosphere and changing patterns of temperature and rainfall. The fresh evidence could help us understand how Earth responds to human influence and shift the baseline of human-ecosystem interactions used in most climate modeling today.

—Kristen French

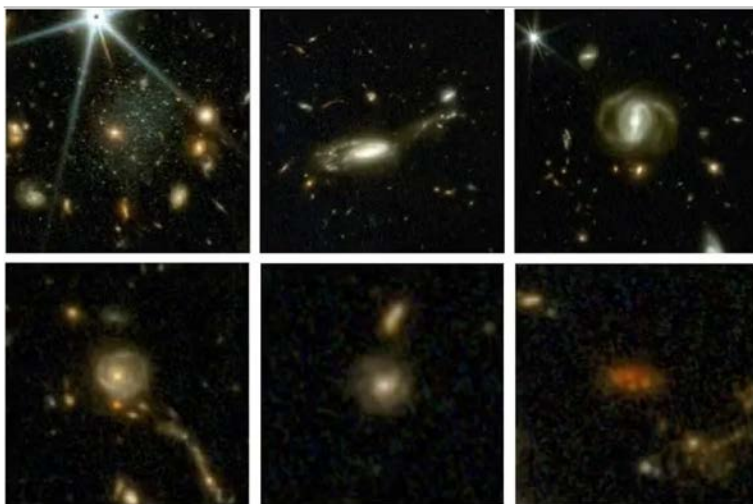
ASTRONOMY

Rethinking the Big Bang

ASTRONOMERS RECENTLY PUBLISHED the largest map of the universe, stretching back more than 13 billion years, which revealed a surprise: Many galaxies were already highly evolved at the earliest phases of the universe—many more than predicted by the Big Bang theory. The new results will be used to modify the Big Bang theory so it better matches what's observed, says astrophysicist

Jeyhan Kartaltepe of the Rochester Institute of Technology. "What we have to tweak is our understanding of how stars formed in the very early universe, what the physical properties were of that initial gas they formed out of, and how rapidly they formed."

Kartaltepe and University of California, Santa Barbara physicist Caitlin Casey have been working together for two years to turn raw data from the James Webb



STARRY SKIES Six images of galaxies taken from nearly 800,000, from upper left to lower right: the present-day universe, and 3, 4, 8, 9 and 10 billion years ago.

The map contains vast “galactic walls,” sheet-like structures of concentrated galaxies, and voids of empty space.

Space Telescope into an image of the universe across deep time that anyone can explore. The final result of this project, called the COSMOS-Web field project, is now online: a composite of 800,000 glittering galaxies.

Thanks to the James Webb’s more powerful mirror and advanced observing techniques, this new image is over 150 times larger than an earlier version created by Hubble in 2004, and shows close to 80 times more galaxies—many of them much like our own Milky Way.

Astronomers have long thought that the oldest galaxies in the universe formed a few hundred million years after the Big Bang, which happened 13.8 billion years ago. So Kartaltepe and Casey were surprised to find that so many of these galaxies were already highly-evolved by 13.5 billion years ago—with well-defined structures and older stars—and that some had light spectrums that showed supermassive black holes at their cores.

This suggests the galaxies formed much earlier than expected and so the Big Bang theory will have to be adjusted, Kartaltepe says. She also hopes the individual James Webb observations in the mosaic image will be used as an online resource by astronomers studying the evolution of galaxies: The sample set of 800,000 galaxies is so large that it includes numerous examples of almost every type of galaxy, at almost every stage of evolution.

“Deep Field” images like the COSMOS-Web image not only tell the story of the universe, they can also help us locate our own galaxy in space and time. The vast scales mapped in the image, roughly 13.5 billion light-years, which reaches to the farthest and oldest galaxies in the universe, is unprecedented. The map contains evidence of vast “galactic walls,” sheet-like structures of concentrated galaxies, and voids of empty space.

One such wall is the Sloan Great Wall, about 1 billion light-years away and the largest known structure in the universe. But every branch and node of the cosmic web seems to be slowly collapsing under the effects of gravity, while the voids grow ever larger.

“The voids push galaxies out,” explains astrophysicist Noam Libeskind of Germany’s Leibniz Institute for Astrophysics in Potsdam. “They are like balloons being inflated.”

The universe is in flux, as is our understanding of it.

—Tom Metcalfe



ENVIRONMENT

How Waves Shape the Planet

W

HEN WIND BLOWS across the ocean's surface, it forms a wave. A single wave can travel thousands of miles before breaking on land; for example, some waves generated off the coast of New Zealand roll all the way to the West Coast of North America, taking up to two weeks to reach their final destination. And while small waves can move as slowly as 5 miles per hour, tsunamis in the middle of the Pacific Ocean reach speeds of 600 miles per hour.

As they move across the planet, waves transport nutrients, plankton, and other building blocks of marine life. They also carry larger animals, including baby sea turtles, who use waves to orient themselves perpendicular to the shore as they push out to sea after hatching on beaches. People, too, use waves to navigate. Some Pacific Islanders are reviving a traditional practice called wave piloting, in which navigators chart a course in part by feeling the waves beneath their boat.

Waves also impact life on land, tossing sediment onto shore that eventually becomes beaches and dunes where shorebirds and other wildlife find refuge. In Germany, where photographer Sandra Bartocha made this long-exposure image at sunrise, waves deposit up to 13 feet of sand per year in some locations and erode up to 8 feet or more per year in others. Whether waves give or take, their impact on the world's oceans is, shall we say, unwavering.

—Skylar Knight & Krista Langlois
Photo by Sandra Bartocha

This story originally appeared in bioGraphic, an independent magazine about nature and regeneration powered by the California Academy of Sciences.



SEA BEYOND

From the ocean we have to the ocean we want

Sea Beyond is the educational programme promoted by the Prada Group and UNESCO's Intergovernmental Oceanographic Commission (IOC), to raise awareness on sustainability and ocean preservation. The programme recently extended its scope beyond education, with two new areas of focus related to the ocean: support for scientific research and humanitarian projects. Sea Beyond is funded by 1% of Prada Re-Nylon collection revenues.

Dive into Sea Beyond's world:
pradagroup.com/seabeyond

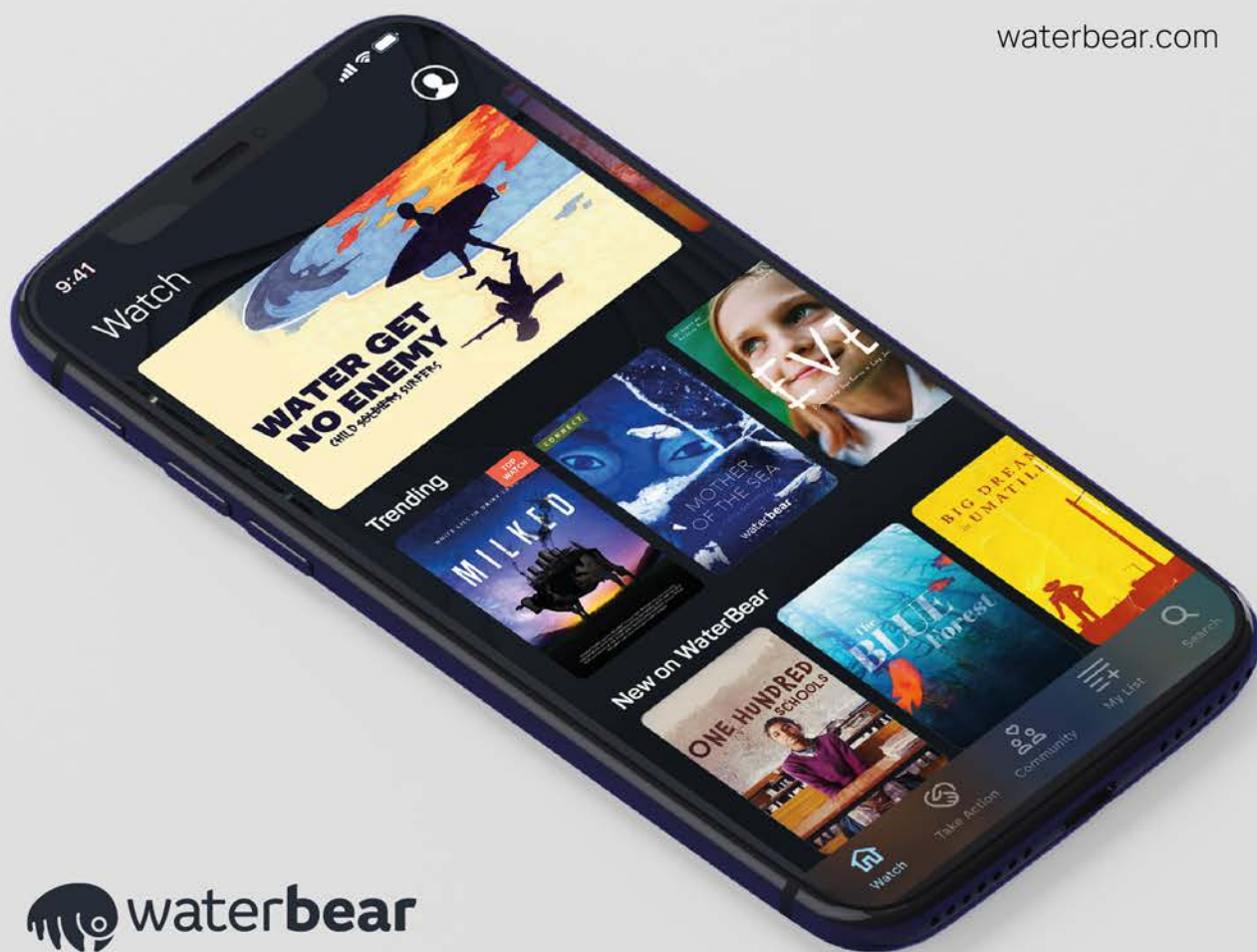


2021 United Nations Decade
of Ocean Science
2030 for Sustainable Development

PRADA Group



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We're All Connected

BY KATHERINE HARMON COURAGE

WHEN THE MARVEL BOYS, ages 4 and 9, get tucked into bed at night, their mother reads them hero stories. Tales of adventure, yes, but more important, of bravery. “There are no stories where the hero is faced with a challenge and says, ‘Nah, seems too hard,’” she told editor at large Kevin Berger recently. This is by design. Because their mother is Kate Marvel, a preeminent climate scientist and author of the new book *Human Nature: Nine Ways to Feel About Our Changing Planet*. And she knows how she wants her children to feel about it.

There are lots of ways to feel. Writer and illustrator Kendra Greene feels it, too. She skipped telling her nieces a bedtime story not long ago, on a visit to see them in her home state of California. Instead they ventured out, into the dark outdoors to inspect impacts from the day’s “wind day.” School was canceled. One day, then the rest of the week. Fires spread. Childhood homes, parents’ childhood homes burned. It felt like a strange sense of recognition. “I don’t know if we’ve ever really told the nieces about the drought their father and I grew up in,” she writes, “that I knew the word drought since forever.” This lifelong knowing, of droughts and wildfires, “marked me as a Californian, like my nieces, like my great-grandmother.”

These generational touchpoints belie our caring, our focus. And our default human animalness. Climates, of course, when you push the mind, are vast. In terms of scale (the universe itself may be its own constantly shifting climate); time (the millions of years for Earth to thaw from an ice-covered globe); and complexity (all of our energy-hungry computers still can’t fully model our planet’s near-future climate). They are also full of mystery and wonder (as Marvel meditates on in her book, excerpted in this issue). And sometimes, of strange promise. I read recently of one good place to go looking these days for increasingly rare orchids: overgrown cemeteries. The generations that came before helping to remind us, in a way, that it’s all, after all, connected. 🌻

ILLUSTRATION BY DEENA SO OTEH



You Have Never Felt Climate Change Like This

Earth scientist Kate Marvel gets personal about climate science

BY KEVIN BERGER



TO UNDERSTAND CLIMATE CHANGE is to understand the magnificence of life on Earth. You can't know what's wrong until you know what's right.

Let's talk about the beauty of greenhouse gases. Before the Industrial Revolution.

Everything radiates light into the world. There are two kinds of light, visible and invisible. The invisible includes infrared light, emitted by Earth into the atmosphere, the column of sky above us.

Here's Earth scientist Kate Marvel:

"We exist only because the sky does. A tiny fraction of our atmosphere consists of molecules that absorb infrared light. These are the naturally occurring greenhouse gases: water vapor, carbon dioxide, methane, and nitrous oxide. They capture Earth's outgoing light because they can dance."

When the dance stops, light is spread out in every direction. Despite making up less than half a percent of the atmosphere, natural greenhouse gases raised the planet's temperature to 60 degrees Fahrenheit. That was the recipe for us. The laws of physics are some strange magic.



CLIMATE OPTIMIST “If you say people are bad, we’re all doomed,” says Kate Marvel, “then you don’t have to think about the terrifying range of possibilities that we could do something.”

Marvel again:

“Take one ordinary star. Add a small rock 94 million miles away. If the rock is too cold, add a sky. Then watch as the magic happens. The sun shines, the planet tries to return its borrowed light to space, and little dancing gases in the atmosphere play a constant game of catch and release, throwing some of the outgoing light back down to its surface. The temperature rises and stabilizes, the rock swings round its mediocre little star, and all the stories on Earth begin.”

Marvel always wanted to tell stories. She started college focused on English and history. An astronomy class opened her eyes to the power and mystery of physics, and she earned a Ph.D. in theoretical physics at Cambridge University. Under England’s cloudy skies, she realized theoretical cosmology was not a sunny job industry; plus, she wanted to do something useful for the world. She struck up a conversation with a famous climate scientist. “What are you, stupid? Go work on climate,” he told her kindly.

She did. “I thought climate science was the most interesting thing in the world,” Marvel said to me recently. (Today she is a research scientist at NASA, speaking for herself, not the agency.) “This is what I had to write about.”

This June, Marvel published her first book, *Human Nature: Nine Ways to Feel About Our Changing Planet*. It’s the most original book on climate science I know. It makes you feel as much about the climate as the change. And the change is charged with emotion. The book is structured in nine chapters, each named for an emotion, including wonder, anger, hope, and love. Aren’t scientists supposed to be neutral and objective? “I can’t be,” Marvel writes. “I need to declare a conflict of interest regarding Earth: Everyone I love lives here.”

ELISABETH SMOLARZ

“Scientists don’t know everything, it’s true. But my God, we don’t know *nothing*.”

Marvel writes with a naturally wry tone, as much novelist as scientist. She blends stories from movies and ancient myths into her explications of the natural forces that make Earth habitable, and the human forces making it less so. At one point, Marvel breaks into a screenwriter and offers a sample script.

INT. UNITED NATIONS BREAK ROOM—DAY

The WORLD LEADERS are milling around after a long shift at the UNITED NATIONS. The room is slightly too small for such a large crowd, and somebody (probably the SWEDES) has finished the entire pot of coffee and forgotten to make another one, so there’s only the orange-lidded decaf pot left. But no one seems to mind. The mood is cheerful. It’s been a successful meeting.

HEAD OF THE AFRICAN UNION

I’m so glad we solved climate change. That was a close one!

POPE

Yes, we should always listen to the scientists. It was very nice of them to warn us.

“Listen to the scientists.” Hahaha! Good one, Kate.

In 2019, Marvel testified at the U.S. House of Representatives. She explained to Congress members that human activities—primarily burning fossil fuel—have increased atmospheric carbon dioxide levels by 45

percent since the beginning of the Industrial Revolution. The increase has raised global temperatures and sea levels, intensified hurricanes and wildfires. Current trends of burning fossil fuel “will be at best economically devastating for many, and at worst catastrophic for all.” As a scientist, she said, “I can only tell you what the climate consequences of those choices might be. As a human being and a citizen, I hope that we will seize the opportunity to create the future we want.”

A Republican then took the floor to extoll coal power and oil drilling, Marvel writes in *Human Nature*. A Democrat got up to read a trite expression of concern. Marvel shares what she was thinking: “For God’s sake shut *up*.” It’s “clear these people require nothing from me, so I let my mind wallow for a bit and am surprised by the intensity of what bubbles up.”

What bubbles up is anger. Yes, scientists are supposed to float above personal biases and politics, Marvel writes. “But I don’t think that we enhance our credibility by pretending we feel nothing when we are ignored or belittled or insulted. It hardly makes us more honest to lie about our emotions. So here it is: I’m *mad*. I am angry at the cynicism, the lies, and the greed. I feel burning rage when I hear the same tired talking points, the falsehoods repeated credulously by people who should (and do) know better. I’m annoyed at how I and my fellow scientists have been treated. And I am absolutely furious when I see the uncertainty inherent in the scientific method twisted into something evil. Scientists don’t know everything, it’s true. But my God, I want to scream, we don’t know *nothing*.”

“I’ll tell them that we humans must constantly tend to these bonds, thinking and changing.”

Writing can exorcise anger and apparently has for Marvel, who was sanguine during our conversation. I was the one fuming about the Trump administration taking an ax to climate change research and gutting environmental laws. As other wealthy nations invest in clean energies and gear up to retire fossil fuels, the U.S. is now driving a 1963 Chevy Biscayne that belches smoke and couldn’t be prouder and smugger about it. How does Marvel, who has devoted her life and career to producing painstakingly clear science that shows Earth is warming to life-threatening proportions, deal with this madness?

“This is not my first rodeo,” she replied calmly, harkening back to her Congressional testimony six years prior. “It’s a different flavor of the same thing. In that sense, I feel like, all right, we’ve done this before, we can get through this. People are still taking big, damaging, stupid swings at us. And they matter. They matter so much. But when you look at the people doing the actual nitty-gritty work of climate research, who are keeping the big picture in mind, I find that nourishing, even healing. I feel a deep sense of satisfaction being part of that.”

Marvel said she has been finding sustenance in the books she has been reading to her sons, aged 4 and 9. “The books always have this hero’s journey structure. There are no stories where the hero is faced with a challenge and says, ‘Nah, seems too hard.’ People do meet challenges, and that’s what I’m hanging on to.”

The sense of pride in doing good science is a wonderful quality of *Human Nature*, I said to Marvel. “I was

thinking of the photographer who takes a picture of the Sistine Chapel so that everybody can see it,” she said. “I’m not likening my book to the Sistine Chapel! But I wanted to show this incredibly beautiful thing that humans have done in understanding the Earth.”

Besides, being a scold is the surefire wrong way to talk about climate change. “People are primed, ‘Oh, you’re a climate scientist, you’re going to come in guns blazing, you’re going to go through my trash and see if I’m recycling, and then you’re going to shame me,’” Marvel said. “But if you start with something like the fact that water on Earth came from space you plug into a primal curiosity that people have, a primal wonder of the world. It always blows my mind how powerful greenhouse gasses are. In the pre-industrial atmosphere, they’re less than a third of a percent, but they’re powerful enough to warm the Earth up. To know why the planet has a temperature at all is to me a good entry into the conversation.”

I was curious what Marvel thought of the criticism from self-styled climate realists, who admit humans are warming the planet but assert the problem is overblown. The thinking goes that public policy should direct resources to social problems like economic disparity and a cure for malaria rather than climate.

“I hope I am never elected to a world government that allocates this much for malaria and this much for climate change,” Marvel said. “But what I do know is that climate is the stage on which everything happens. The play and the actors and the weather may change, but climate is the stage. It’s the stage for agriculture,

transport, trade. Changes are happening to the stage for virtually everything on Earth.”

What Marvel finds offensive, she said, is critics’ insidious practice of cherry-picking natural uncertainties in science to claim scientists can’t be confident that climate change is causing extreme weather. The criticism goes that deadly hurricanes, floods, and wildfires in recent years have merely been “seasonal weather events.”

“It’s just nonsense,” Marvel said. “The ‘Climate Trends’ chapter in the U.S. National Climate Assessment says there is no detectable trend in the number of hurricanes, but there is a detectable trend in the number of extreme hurricanes and how fast they’re intensifying and how long they are lasting before they dissipate. I know that because I wrote it.”

Consider the recent, catastrophic floods in Texas. “It’s not new, shiny, cutting-edge science,” Marvel said. “This is physics so basic you can see it in everyday life. We know there’s more evaporation off warm water. A hot shower is going to fog up your bathroom more than a cold shower. When the ground is hot, that makes the air more buoyant and makes it rise more and so you get unstable conditions that lead to more precipitation, more storms. So, all these very basic physical things combine to prime the atmosphere for these heavy downpours we have been experiencing.”

The canard that we need not worry now about climate change because people in the future will solve it, Marvel said, reminded her of an old joke. “A drowning man prays to God for help. A ship comes by and offers to rescue him, and the man says, ‘No, I’m waiting for God to save me.’ Another ship comes by and he says, ‘No, I’m waiting for God.’ And another ship comes by and he says the same thing. Then he drowns and goes to heaven. He asks God, ‘Why didn’t you save me?’ And God says, ‘I sent you three ships.’ We have to stop warming. But it won’t be by arguing that somebody’s going to figure it out eventually. We are that somebody.”

Marvel calls her book *Human Nature* to upend the belief that human nature is immutable, or more to the point, immutably bad. “I’ve had so many people tell me, ‘Oh, human nature means we can’t solve climate change because we’re too selfish, we’re too bad,’” she said. “That’s just another bad way of dealing with scary

uncertainty. If you say people are bad, we’re all doomed, then you don’t have to think about the terrifying range of possibilities that we could do something. You don’t have to face this feeling of, we could do it, but maybe we won’t.”

In “Love,” the final chapter in *Human Nature*, Marvel gets personal about her own emotional decisions as a scientist, wife, and parent. She details her torn feelings over living near wilderness in California, where she was born, and the urban jungle in New York, her husband’s preference. (They live in Brooklyn.) She shares that she was diagnosed in 2022 with a blood clot in her brain, her treatment for it, and the lingering effects.

“I live now in a strange little limbo, never sure whether to expect a sudden catastrophe or simply the inevitable slow decline into something worse than now,” Marvel writes. “This is a feeling for which a career in climate science has prepared me well.”

Marvel’s admission about her health casts a powerful and moving spell over her book. Climate change feels personal and immediate. I asked Marvel why she decided to tell readers about the blood clot.

“I didn’t mean to at all,” she said. “It just kind of came out because when I was writing the last chapter, I wanted to talk about love, I wanted to talk about the interconnectedness of everything. As somebody who grew up with nature, the question that weighed on me is, what is our relationship to nature? Are we part of nature? Are we separate from nature? What does it mean to be reading about the Sierra Nevada mountains when you live in New York City? But going through this scare showed me that question is a silly one, a wrong one. Life is a complex renegotiation of our place in the world every single day.”

Marvel imagines passing that insight along to her sons. “I’ll take them to the mountains and through the city,” she writes. “We’ll talk about our place in the world, the physics that binds us tightly but passively to the whole of nature. I’ll tell them that we humans must constantly tend to these bonds, thinking and changing—as must happen in any relationship that lasts. If you love something, I’ll say, you must allow yourself to feel it. I do. I will.” ☺

KEVIN BERGER is the editor at large of *Nautilus*.

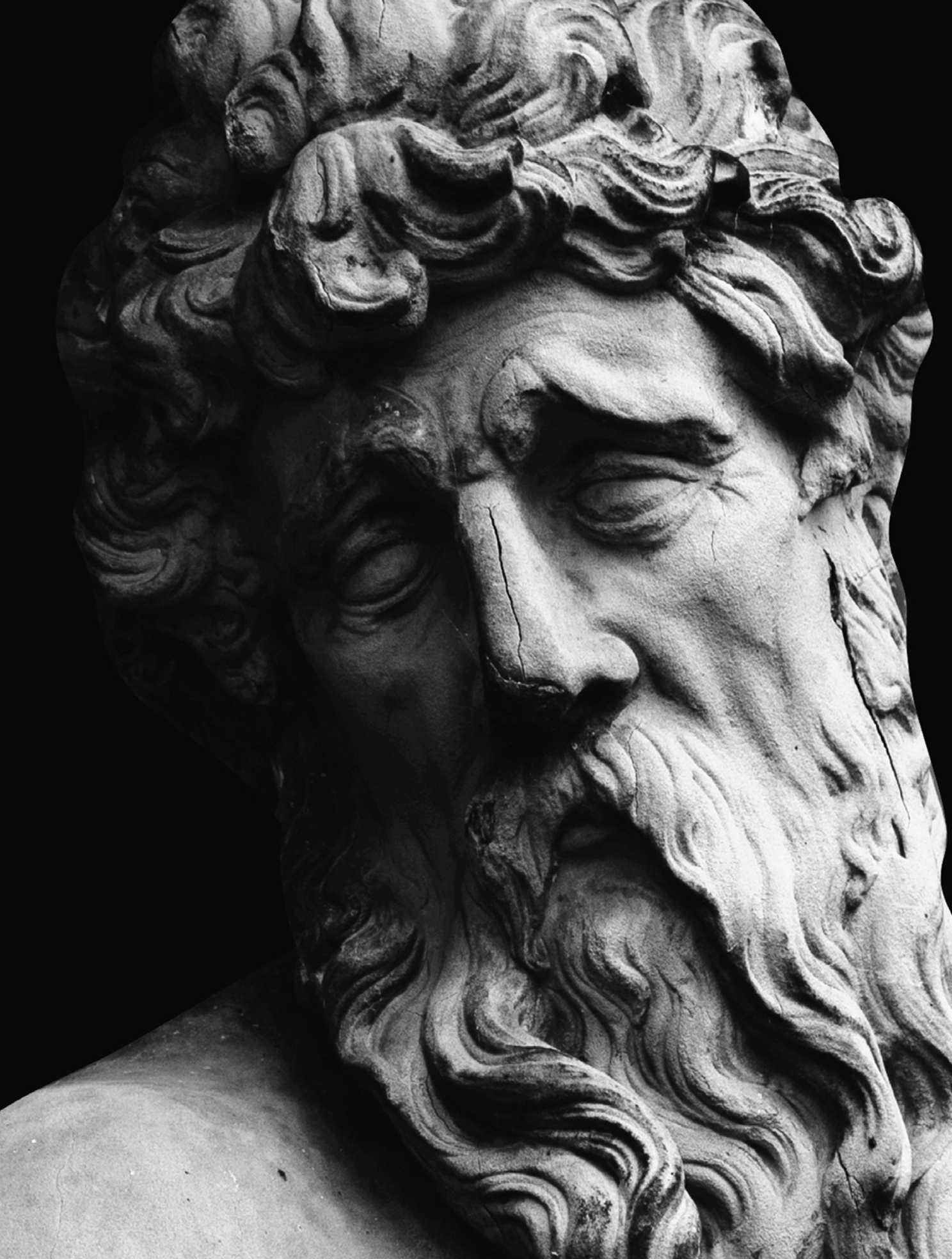
What Poseidon Is Telling Us

*Weather is what humans experience over our short lives.
Climate is a matter for the gods.*

BY KATE MARVEL

ALL THE GODS like to stir things up every now and then. Apollo gives unwanted gifts. Zeus throws tantrums, flings thunderbolts, assaults boys and women. But no one can mess with an island civilization quite like the god of the sea. Poseidon loves this part of the job. All it takes is a little shake of the waters at the surface and the people lose their minds. They pray, they call on heroes, they start sacrificing anything they think might please him. His wife loathes this, starts hollering at him whenever the bloated, fish-bitten corpses of drowned horses and cattle begin to drift down to the underwater palace. What, she asks (not unreasonably), do they think we're going to do with these? Once, the people tried chaining a naked princess to a rock by the sea, which struck even Poseidon as a little weird. He allowed her to be rescued by some hero who probably never shut up about it for the rest of his short life.

Men need to do crazy things for immortality. Gods don't. Time moves more slowly when you're divine. Deep in the dark waters, Poseidon often finds himself behind the times. It takes information many years to worm its way to the depths of the ocean. Sometimes he hears something that makes him rush to the surface, only to find that all those concerned have died. As he descends beneath the waves again, Poseidon watches the constellations blur above the shallow waters overhead and then disappear from view. The stars shine bright over the midnight sea, patterned with stories of heroes long gone.



The ocean is deep; it keeps secrets. Time passes differently in the abyss

All the water in Poseidon's seas was born in that twinkling sky. When a large star dies, it explodes and spreads its guts across space, where they are recycled into new forms and new beings. Oxygen released in the first such explosion combined with ambient hydrogen to make the first water. The water created by many subsequent explosions eventually found its way to us, transported in the frozen surfaces of comets and meteors. This means Earth's water is older than Earth itself. It's probably even older than the sun. In 5 billion years, when the sun exhausts its own fuel, our water will be carried off into the depths of space, ready to nourish some other planet yet to be born.

In the beginning, the new baby Earth was so hot that the water carried by these rocks was turned immediately to vapor suspended in its nascent sky. There would have been no ocean for many years. But then the planet cooled, and the steam cooled and then condensed. There was a primordial rainstorm, which became a deluge and then a flood, covering three-quarters of the planet in water. The oceans came from the sky.

Since then, sea and sky have never lost contact. The ocean absorbs and retains the heat of the sun. It moderates the climates of coastal regions, because water is much slower to warm or cool than land. And the ocean is an effectively boundless source of the water that makes clouds, rain, and snow. The seas are governed by

the same physics as the sky: floating, sinking, moving, turning. Together, these motions help the ocean move heat, salt, and moisture around the planet. No model of Earth's climate would be complete without an ocean, extending the tall columns of atmosphere not just outward into three dimensions but also downward into the deep, letting water rise and sink and flow. The sea and the sky are inseparable. They form the world in which winds blow and rain falls, the background against which life on Earth goes on.

When steady winds blow across the surface of the sea, they drive currents, which twist with the spinning Earth and slam into the boundaries of continents. These form great circular gyres, some parts of which have names. The western boundary of the North Atlantic Gyre, for example, is the Gulf Stream, a northward-flowing saltwater river that travels between 25 and 75 miles a day, bringing warmth from the Gulf of Mexico into the Atlantic Ocean. On the other side of the world the Kuroshio Current brings warm Philippine waters to Taiwan and Japan. As long as the wind blows and Earth turns, these currents will continue.

But underneath the surface, something much more gradual is happening. The overturning of the deep ocean is slower, a conveyor belt driven by floating and sinking. Surface waters move northward until they reach the Arctic, where some of them harden into sea ice. The left-behind Arctic waters are saltier and cold;

both of these properties make them heavy. They sink resignedly down in the cold polar ocean, pressing down on the deeper waters and forcing them to flow. The deep ocean is a river of failed ice, a bottom-dwelling current moving southward, overshooting the warm places, journeying to the southern pole. The waters around Antarctica move eastward and close, unimpeded by land, in a swift and freezing ring. There, they wait for storms and turbulent seas to bring them once more to the surface. Eventually, the water surfaces again and resumes its long, slow movement around the globe. This is called the thermohaline circulation, driven by temperature and saltiness. It takes around a millennium for water to complete its journey to the depths and back. The ocean is deep; it keeps secrets. Time passes differently in the abyss.

And time is what marks the difference between climate and weather. We don't need to know much about the deep ocean, or anything else that works as slowly, to forecast the weather. We just need accurate measurements of current atmospheric conditions. If we know enough about the present, physics will tell us what's coming. The trick is to both gather the right information and hold tight as it's buffeted by the chaos of the outside world. Weather forecasts are excellent a few hours out, good a few days out, and unreliable after about a week.

Climate is the long-term average of weather: the background conditions in which it happens. Like the weather, the climate changes naturally, but this happens over many millions of years as tectonic plates move, Earth wobbles in its orbit, and the deep ocean currents shift. Weather is what humans experience over our short lives. Climate is a matter for the gods. To understand it, you have to understand all of the forces that shape the world: not just the atmosphere, but the oceans as well. No weather model can tell me with any accuracy what the temperature in New York City will be at 10 in the morning two years from today. But I know it is likely to be hot and sticky in the summer and cold and gray in the winter. The New York climate is made by the prevailing winds, a whole continent of land to the west, the chemical composition of the sky, and the slow

The rules, shaped for so long only by physics, are changing now. There are new characters.

circulation of the nearby ocean: things that change more slowly. Things that, in a human lifetime, are not supposed to change at all.

The climate models I use every day tell me why the world is the way it is. They tell me that the planet is spherical, watery, and turning. It's heated by the sun. Air rises from the warm, moist tropics and sinks in the desert subtropics. In sinking, it presses down hard on the surface, forcing the air below to move toward areas of

lower pressure. The world turns beneath the moving air, which is deflected into trade winds. The winds move over the sea surface, shoving the water along at the boundary between ocean and sky. The water obeys, but recalcitrantly, slowed by its own choppy roughness and bent at an angle by the spinning world. The ocean layers below the surface are dragged by the moving current above. Water rains into the ocean and evaporates back to the sky. These are the foundations. You can always add more and more complexity, building the model up further. Add swirling confrontations between stray warm air just up from the tropics and cold air dripping down from the poles. Now add the boundaries of continents. Now add mountains. Now add forests that exhale great breaths of cloud. Now add cities, cars, factories. Now add yourself.

The rules, shaped for so long only by physics, are changing now. There are new characters in the story, entities not describable by the laws of physics but still subject to their consequences. They are tiny but powerful, capable of changing the very sky under which they live. These characters can think and feel and read. They are us. ☺

KATE MARVEL is a climate scientist and the author of *Human Nature: Nine Ways to Feel About Our Changing Planet*. She led the "Climate Trends" chapter in the U.S. government's Fifth National Climate Assessment, and has given a TED Talk, appeared on *Meet the Press* and *The Ezra Klein Show*, and testified before the U.S. Congress. She has written for *Scientific American*, *Nautilus*, and the On Being Project. She lives in Brooklyn with her family.





Marking Time in a Changing World

Climate change is throwing traditional calendars into disarray

BY KATARINA ZIMMER

IT'S NOVEMBER, AND ARLYN CHARLIE feels uneasy. As he steps across the frozen surface of the *Teetl'it Gwinjik*, a river in Gwich'in territory in northwest Canada, the ice cracks beneath his feet.

Around him, poles jut out from holes in the ice; beneath the surface, they anchor nets to catch *luk dagaii*, broad whitefish, as they migrate downriver. For generations, the Gwich'in people have traveled here during *Khaiints'an*, the autumn of their five-season calendar, when the skies grow darker and the first snow falls. They have a slim window of time after the ice freezes over but before the fish conclude their fall run. This brief pulse of fishing provides vital winter sustenance—especially now, with rising grocery prices—and remains a pillar of Gwich'in identity, Charlie says.

Some seasons have disappeared altogether.

But while Gwich'in people used to set their nets in mid-October, the freeze-up has become increasingly unpredictable and sometimes happens as late as November, Charlie wrote after his venture onto the thin ice. And Charlie has noticed snow and ice thawing under an unseasonably warm *Khaiints'an*. While older people seem to know how to read the ice and tell where it's safe to step on, the 28-year-old Charlie treads cautiously. Watching his grandmother take fish from the nets, he wonders whether this timeless tradition might someday become impossible. "There's a lot of unpredictability to everything within our calendar and how we interact with the land now," Charlie says. "How do our cultural and traditional practices remain intact?"

The Gwich'in, like many other Indigenous people, have accumulated a vast body of knowledge on the seasonal rhythms of wildlife, plants, and weather around them. And over millennia, these observations have coalesced into calendars that mark the passage of important annual changes. These ecological or "biocultural" calendars are key to survival, helping people predict the best times for fishing, harvesting, hunting, herding, or planting. Even today, when traditional knowledge systems and ways of life are threatened due to the effects of colonization, these calendars remain important for many Indigenous communities. As

Charlie notes, though many Gwich'in people now live in towns and settlements and not nomadically as they once did, this kind of seasonal knowledge still forms a critical link to their lands and their culture.

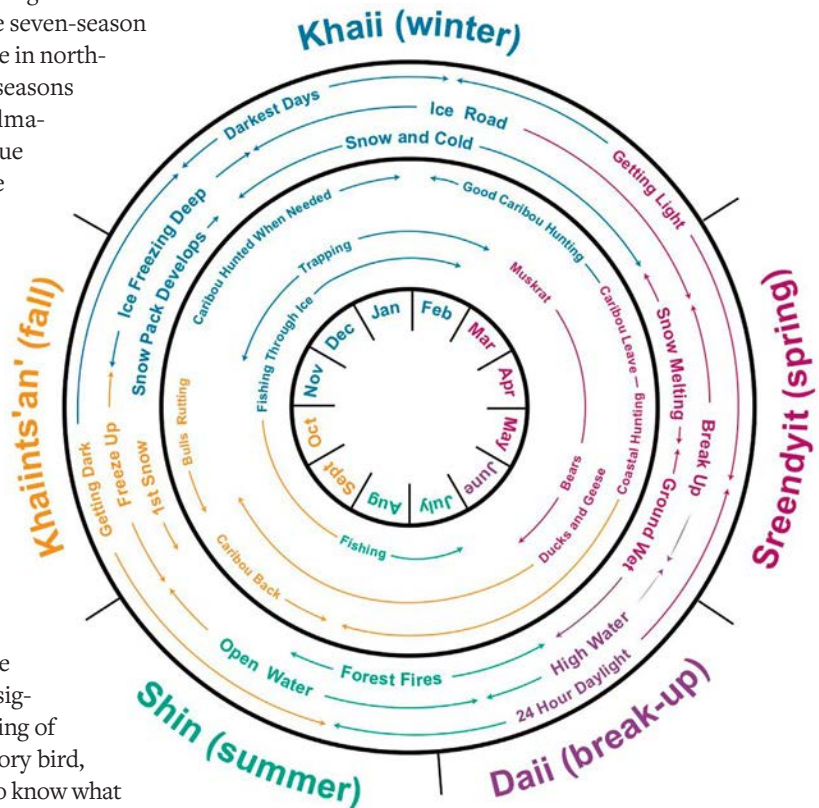
But rapid changes to the climate are disrupting many of the seasonal patterns encoded in many Indigenous calendars. Warmer weather and disrupted cycles of storms and precipitation are transforming the very character of the seasons while also shifting them forward or backward in time. Some cycles that used to be in sync—such as the ice freeze-up and the whitefish migration—now no longer are. Climate change is shifting the schedules of plants and animals, making seasonal events harder to predict and key activities harder to plan. As Western scientists plot the extent and details of these changes, many Indigenous people are feeling them viscerally through their calendars as their practices, identity, traditions, and sense of seasonality are disrupted.

Seeking a way forward, some communities are exploring ways of adapting their calendars to new conditions so they can continue their traditional ways in a warming world. "As Gwich'in people, we have this idea that we are spiritually connected to the land," Charlie says. "We still want to rely upon it. We still want to trust that we can harvest and travel out on the land [safely]."

MANY URBAN SOCIETIES with industrialized food systems have become divorced from the rhythms of nature; some scholars have described the Western concept of time like an arrow—a linear constant, steadily counting the months, years, and decades. But many cultures closely attuned to nature, including many Indigenous communities, have a more cyclical perception of time that is rooted in the rhythms of their lands, though they often also track astronomical observations such as the lunar and solar cycles. Ecological calendars are as diverse as local ecologies and cultures themselves—ranging from the seven-season calendar of the Larrakia people in northern Australia to the 72 microseasons of the ancient Japanese almanac. “It’s representing a unique knowledge system from one language group that exists in one place,” says Emma Woodward, a community-engaged geographer at Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO) who has been helping to conserve Indigenous calendars in northern Australia.

Over generations, many Indigenous people have learned to recognize the broader significance of signals around them—the flowering of a plant, the arrival of a migratory bird, a shift in the winds—not just to know what season it is, but also what they need to be doing to survive as seasons change. In the Larrakia calendar, for instance, the blooming of wattle flowers during the season of *Dinidjanggama*, or “heavy dew time,” signals that small sharks along the coast are fat and ready to be harvested. When Anishinaabe communities around the Great Lakes in North America hear frogs singing in the early spring, they know the maple sap harvest is over; if they leave their taps in longer, the sap will

TIME IS A WHEEL Over many generations, the Gwich’in people of northern North America have documented seasonal patterns in environmental conditions and natural events around them, creating an ecological calendar they use to plan seasonal activities. Climate change is disrupting some of these ancient patterns.



become too milky, according to Michael Waasegiizhig-Price, who is Anishinaabe and the traditional ecological knowledge specialist at the Great Lakes Indian Fish and Wildlife Commission. And on the islands of Vanuatu in the South Pacific, people look to the annual mass spawning event of a small marine invertebrate, the palolo worm, to predict the impending cyclone season, allowing them to prepare for it accordingly.

Sometimes these cycles just happen to be synchronized with one another; other times there may be a causal relationship. Where Larrakia elders say that certain flowers call the cold weather, Western scientists might contend that it's the cold that induces the flowering, says Lorraine Williams, a Larrakia woman who works on research projects about traditional ecological knowledge at Charles Darwin University in the Northern Territory and with CSIRO. She says that traditional knowledge provides a different way of looking at nature.

Knowledge of these ecological connections are typically passed down through Indigenous language and culture. In several Indigenous languages of the North American Pacific Northwest, the name for the Swainson's thrush translates to "salmonberry bird," relating to traditional wisdom that the bird's song will cause the berries to ripen in the late spring and summer, says linguist David Stringer of Indiana University. And in Brazil, during annual festivals celebrating the dark-billed cuckoo, the Wajãpi people sing a song that guides the planting of sweet potatoes: *When a breeze blows at the beginning of the dry season, and the stars of the Pleiades appear in the early morning, then the cuckoo starts to drink and sings his drunken song. He sings until the end of the growing season, when the sweet potatoes begin to sprout, and then the Pleiades will appear in the evening sky,* according to a summary by Stringer.

The cultural transmission of calendar knowledge is threatened by the declining use of many Indigenous languages that have passed that knowledge down over the generations. Knowing and communicating when to plant crops or hunt wildlife allows communities to maintain sovereignty over their food production and access healthier and less expensive options than products in the supermarkets of industrialized food

systems. "It's a matter of community health, it's a matter of social justice," Stringer says. On Aneityum, an island in Vanuatu, lobsters are traditionally only allowed to be collected during the three months when a deciduous tree called *Terminalia catappa* loses its leaves, preventing overharvesting. And while the palolo worm warns of dangerous cyclones, the browning of the leaves of the coastal she-oak, *Casuarina equisetifolia*, alerts people to the risk of heatstroke.

Though this kind of relational guidance may seem foreign to non-Indigenous people, many European cultures used similar signals to time agricultural activities until quite recently, Stringer says. For instance, according to a 1976 poem from Warwickshire, England, it's time to sow barely when an elm leaf is as big as a mouse's ear, and when it's as big as a shilling, it's time to plant kidney beans. It's just that urban societies, so separated from their food production systems, have largely lost this practical knowledge.

And as climate change gathers pace, much of the traditional calendar knowledge is becoming less reliable.

Indeed, in Yuku Baja Muliku country in eastern Australia, some locals have reported that the delayed flowering of wattle trees is already a less reliable signal for the beginning of the fishing season for certain species. Similarly, some Indigenous communities in northern Chile have noticed that the buff-necked ibis, a migratory wading bird whose arrival has long marked the beginning of spring and the time for fishing king crab, now appears several weeks earlier or doesn't migrate at all, according to the Chilean ecologist Ricardo Rozzi of the University of North Texas and the Universidad de Magallanes who directs the Cape Horn International Center. Although such signals have been replaced with government regulations to time the fishing season, "there is a loss of this local, more precise sign for the beginning of the spring," he says. There are also concerns that some indicator species might be directly threatened by climate change, Williams adds. "At the moment, we've got the traditional markers and indicators of when to go and hunt a certain species. What if those species don't exist anymore? Are they going to have a different story?"

Planetary warming is disrupting many of the seasonal patterns encoded in Indigenous calendars.

The decoupling of natural cycles can have a range of cascading consequences. For the Gwich'in, it threatens people's safety on the ice as well as an important cultural tradition and access to food. And on the southern Chilean island of Chiloe, Mapuche people have long harvested the leaves of local seaweeds to fertilize freshly planted potatoes. But because the oceans are warming faster than the land, the seaweed leaves now emerge about a month sooner than the potato planting season, Rozzi says. So they now have to store the seaweed until planting begins, which means the seaweed can start to rot prematurely, he adds. "It's creating new complications."

By disrupting links that have held steady for generations, climate change is making seasonal patterns unpredictable, especially at high latitudes that are warming faster than the rest of the globe. "We cannot really depend upon the patterns of long ago," Charlie observes.

Unpredictable weather is one of the biggest challenges faced by the reindeer-herding Saami people who live in northern parts of Norway, Sweden, Finland, and Russia. Within their calendar, the Saami have documented certain weather patterns that they have observed often correlate with one another. Saami herders have long used these observations as weather prediction tools to help them plan when and where to guide their reindeer, who provide them with sustenance, clothing, and trade. For instance, a warm and cloudy New Year's Day traditionally predicts a good, green summer, while the weather on the last summer

night, in mid-April, foretells the weather for the entire spring, says Klemetti Näkkäljärvi, a Finland-based Saami anthropologist who studies Saami culture. But "these examples ... do not correspond to current conditions and cannot be used to predict the weather," he says. In the Saami's view, these tools have become so unreliable that they're no longer taught to children. The greater unpredictability makes it harder to guide reindeer to good pastures, and also creates uncertainty around the freezing of waterways—increasing the incidence of accidents where ATVs, snowmobiles, and even reindeer have dropped through the ice, Näkkäljärvi says.

Unpredictability in the climate is mirrored in animal behavior, which can make hunting using traditional knowledge less successful. The Tahltan people of the Canadian subarctic have long used a specific window to hunt moose: when the animals come down into the valleys after spending the summer in the mountains, but before their mating season begins, explains Curtis Rat-tray, a Tahltan community leader and the co-founder of the Tü'desē'cho Wholistic Indigenous Leadership Development in British Columbia. But nowadays, "the moose are staying high up in the mountains longer than usual," he says. Even at the relatively high elevation of his aunt and uncle's hunting camp, it's proven harder to bag moose. That's a problem because hunting remains an important source of sustenance, especially as community members experience higher grocery prices, while elders are worried about losing a key cultural practice. "They've seen how much our culture



REINING IN UNCERTAINTY

Saami people depend on rhythmic signals in their environments to guide their herding of reindeer, which provide sustenance, clothing, and trade.

has changed, and how much people are more and more dependent upon the wage economy and less and less on the other traditional activities,” Rattray says. “That’s the concern that they’re having: that climate change will make maintaining our cultural practices even more difficult.”

Changes to the timing of natural cycles and decoupling of ecological events are happening on top of the more direct assaults of climate change on Indigenous time-keeping systems. In a major alteration to Saami calendars, some seasons have disappeared altogether—for example, “autumn-winter,” a cold but snow-poor transitional season that has been swallowed by longer and warmer autumns, Näkkäläjärvi says. “When the intermediate seasons disappear, it’s like an identity crisis: What are we, if not a people of eight seasons? Part of the uniqueness of Saami culture and environment is lost.”

Across many cultures, the changing character of the seasons is threatening all manner of seasonal events and traditional practices

IGOR STOMAKHIN / SHUTTERSTOCK

enshrined in Indigenous calendars. Drier autumns bring fewer mushrooms for the Saami's reindeer to eat, and harsher than usual winters and springs have killed countless herd members. Arctic heatwaves, meanwhile, have made it harder for the Gwich'in to preserve whitefish they catch in the summer, while sudden floods have washed away a fish camp built by Charlie's great-grandfather. And around the Great Lakes, Waasegiizhig-Price says that less and later snowfall is disrupting important storytelling practices enshrined in Anishinaabe calendars; traditionally, tales of the trickster hero Nanabozho, whose antics help teach kids morality and ethics, are only told when there's snow on the ground. "What happens if one year we don't have any snow at all?" Price asks. "It's a big question among a lot of traditional storytellers and knowledge keepers."

ANISHINAABE AND MANY OTHER Indigenous communities are exploring ways of adapting their traditions to new conditions. Recalibrating their calendars can be a key part of this adaptation—not only by tweaking the timing of cultural practices to ensure better conditions or escape climatic vicissitudes, for instance, but also relearning and sharing new patterns and behaviors of creatures on the landscape, Waasegiizhig-Price says. "Indigenous peoples have been resilient for thousands of years, and our culture and our traditions allow us to adapt to those harsh climates," he says. "We're going to have to evolve our ways of seeing and our ways of knowing as well to a changing climate."

That's the goal of a climate adaptation project led by Cornell researcher Karim-Aly Kassam. In two Native American communities as well as three Indigenous villages in Tajikistan and Kyrgyzstan in Asia's Pamir Mountains, he and his colleagues have helped people document their calendars so they can introduce them into school curricula. Children can help update these calendars, boosting their connection to their habitat as well as helping their communities adapt, says Kassam. "We have to root the adaptation strategy in the local ecology and the local culture, so it makes sense, so it has relevance."

Adaptability is, in some sense, a baked-in feature of many Indigenous calendars. Rather than using the same date every year to plant crops, for instance, relying on a wild plant's flowering time accounts for the variability in weather, shifting with environmental conditions in the same way that crops do.

Because of this self-adjusting nature, many seasonal shifts in Indigenous calendars only become obvious when they're compared with more consistent ways of timekeeping, Waasegiizhig-Price says. "Comparing the changes on the landscape with the movement of the stars will tell us the extent of the change that's going on with the planet, much like looking at a Gregorian calendar," he says.

This calendar flexibility is already helping some communities adapt to a changing climate. In Vanuatu in the South Pacific, which is experiencing increased variability in rainfall, many of the 159 documented calendar-marking plant species still serve as reliable agricultural indicators, says ethnobiologist Neal Kelso who has been helping to study these plants for five years. A few years ago, a very rainy season pushed back flowering of certain calendar plant species by a week or two, so locals planted their crops later. "Even though ... most people have smartphones and are aware of the Gregorian calendar and know that the flowers are flowering later, they still decided to follow these signals, and the crops still did just as well as they always do," Kelso says.

The Gwich'in, meanwhile, may eventually have to adjust their calendars—and turn to other ways of fishing if the ice no longer forms during *Khaiints'an*, Charlie says. Often, "we forget that there's people that still rely upon these environments," Charlie says. "What happens to their environments and their lands has a great effect on their identity." The rapid pace and ecological upheavals of today's climate change will continue to push these inherently flexible calendars—and the cultures that have built and maintained them—to evolve in step with the shifting rhythms of the Earth. 🌀

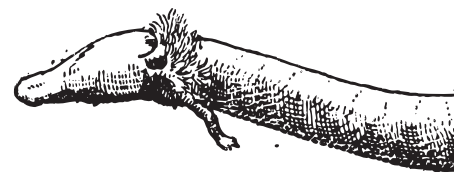
KATARINA ZIMMER is a freelance science and environment journalist.



In the Land of the Eyeless Dragons

The cave-dwelling olm is a canary in the coal mine for environmental change

BY GARY HARTLEY



TO GET TO KNOW THE OLМ, Europe's only exclusively cave-dwelling vertebrate, you need to meet it on its terms. Extremely particular terms.

The pale, eyeless salamander (*Proteus anguinus*), once thought to be the offspring of dragons, can live for up to a century. It only lives in deep cave systems, hundreds of feet underground, where light doesn't reach, in countries across the north Mediterranean and the Balkans. It is long and thin, growing up to about a foot in length, with stunted limbs and a somewhat sedentary lifestyle. It is sensitive to sound, vibrations, pressure changes, temperature, electromagnetism, and the intrusion of light, and it only appears above ground when washed to the surface by high waters.

It is, thus, not exactly the easiest study species—but this hasn't deterred Gregor and Magdalena Aljančič. The husband-and-wife team spend a fair amount of their time in the pitch-dark, under Kranj, Slovenia's fourth-largest city, the railway and old road to the capital rumbling above. Their cave laboratory, established by Gregor's father, Marko, in 1960, can be entered through an inauspicious metal door on an industrial estate. Far from your typical scientific establishment, its natural cave walls are covered in rare species of crickets and spiders, and only phone flashlights are allowed to light your way around. It's a haven for 20 of these olms, living in specially made pools.

Technological advancements in this subterranean are something of an Aljančič family preoccupation. Upgrades have included using a vintage, 8-bit ZX Spectrum computer connected to a camera as part of a high school project in 1989, a low-resolution CCTV-style system in the late '90s, one of the earliest examples of biological video-tracking in the early 2000s, and the last major advance in 2009, when a digital infrared video system was put in.

All of this has yielded important insights, including on the olm's sensitivity to the Earth's magnetic fields and its reproductive behavior. But work in a lab, however creatively constructed, can only get you so far.

Testing water using environmental DNA technologies has allowed scientists to learn more about where olms make their dark homes. Scientists have also discovered how much these reclusive animals are impacted by goings on at the surface; although they can live nearly a thousand feet below ground, olms are threatened by water pollution and construction and deforestation in large parts of their range. And a warming climate looms large over their fragile cave ecosystems, as they and other species there depend on a consistently cool temperature. To truly understand the curious amphibian and the threats it faces, though, there's a need to go deep, literally. And perhaps unsurprisingly, the Aljančičs have a plan for that.

WHY SUCH EFFORT for a strange species barely known outside a handful of countries?

The olm's striking biology, which also includes the capability of going for years without eating and having one of the largest—albeit currently unsequenced—animal genomes, offers potential insights that could change medicine. Its life (and death) also exposes otherwise hidden impacts of human activities happening right now, and their damages.

Karst, the Slovenian-born name for the limestone landscapes home to olms as well as many other rare and unusual species, covers 20 percent of the world's terrestrial surface, and its groundwater provides anywhere from 20 to 50 percent of drinking water for people. It is easily carved by water, creating essential aquifers—including the Edwards Aquifer in Texas—as well as elaborate caves, such as the Mammoth Cave system, which runs more than 400 miles in Appalachia. It also harbors countless isolated caves. All of these hidden ecosystems can help provide answers to great questions of evolution, ecology, and climate adaptation.

Despite containing such life-sustaining commodities and tantalizing potential for discovery, subterranean karst ecosystems remain severely understudied compared to other biomes. This is especially striking, given that they face considerable threats from intensive





STRANGE SCIENCE

Wife and husband team Magdalena and Gregor Aljančič have devised a wide range of creative solutions for studying the elusive, sensitive olm. They do most of their work here, in their cave lab in Slovenia, which was originally set up by Gregor's father in the 1960s.

farming and industrial development, which can cause pollutants to leach into groundwater—an issue that also contributes to olms, and many other cave-dwellers, being on a downward population trajectory.

Cave specialist animals provide a barometer of ecosystem health, and olms in particular, with their decades-long lifespans, can act as a living gauge for groundwater quality and other disturbances, tracking the historic presence of pollutants right up to the present. A proverbial canary in the karst cave.

“Even though *Proteus* is only endemic to dynamic karst in our region, karst itself is everywhere,” says Magdalena Aljančič, whose day job is with the Karst Research Institute in Postojna, home to Slovenia's largest known olm population. “Sometimes you need such a charismatic species to better put your message across.” And,

yes, to many people, the olm is the picture of charisma; its image once graced Slovenian coins, is used as a poster-animal for local ecotourism, and even spawned the name of that country's oldest science magazine, *Proteus*. So, here, its survival has an added cultural urgency.

WITH WATER SECURITY and biodiversity high on political agendas in Europe, now might well be the olm's moment. And substantial developments in monitoring technologies over the past decade offer the chance for olm research to make a great leap forward: the creation of a “virtual lab” in the karst underworld.

“The main reason for building the cave laboratory 65 years ago was to circumvent the inaccessibility of *Proteus*' natural habitat and allow long-term observations under more controlled conditions,” says Gregor Aljančič.



TOMAZ BUKOVEC

Once thought to be the offspring of dragons, olms can live for up to a century.

“Of course, there has always been as much fieldwork as possible as caves are the ultimate place to test laboratory observations, but this can be dangerous,” he says. He would know, having experienced a lucky escape after a close call during a cave dive collecting olms for DNA swabs 10 years ago. After losing the safety line, with his oxygen rapidly running out and his family fearing the worst, he just managed to escape to safety. “With advanced technologies, the idea of studying olms in the wild is becoming more and more realistic. The new approach would not only be more efficient but could also save lives.”

The Aljančičs have mapped out plans for something they are calling the ProteusWatch Virtual Lab. It would recreate almost all of the experimental capabilities of their home Kranj cave lab—except that the humans would be far, far away from their study subjects. The in-the-deep-wild lab would pair video analysis with machine learning, advanced environmental sensors, imaging sonars, and underwater drones to study the ecology and behavior of olms. This setup could, for the first time ever, allow researchers to record the animals’ activities, sensory capabilities, interactions, foraging, and reproduction—in situ, in real time. A second proposed virtual lab would focus on the groundwater habitat, painting a picture of how healthy and stable these extreme ecosystems really are.

Just assembling these capabilities might be hard enough, but studying these remote cave ecosystems—even from afar—introduces a certain echo from quantum mechanics: the quandary of how much observing might change what is being observed. Whatever technology goes into the chosen deep cave, it must not change the way the sensitive species interacts with its environment, whether that’s from light, vibrations, or electromagnetism. It also must be robust enough to work with infrequent maintenance and in harsh conditions. Training AI also won’t be easy, given that the nearest machine learning models to what’s needed have only looked at surface-living lizards.

Difficult and impossible are different things, however. Especially to the Aljančičs. Solutions are out there, including special cages to block out electromagnetic fields from equipment.



Initial ideas have been explored through the European Union's LifeWatch ERIC program, and new machine learning studies are in progress.

The goal is to make the data from these remote labs freely available. So computer scientists, led by Zhiming Zhao at the University of Amsterdam, are working to make sure sensors, software, and AI are aligned in a central computing infrastructure, enabling researchers to make the best use of the proposed facility. Zhao's team has already created similar Open Science facilities for projects studying ecosystems in the Netherlands and Italy, and for taxa as barely tangible as phytoplankton.

There are several parties keen to get the ball rolling, too, with the governments of Slovenia, Croatia, and Italy all committed to monitoring their olm populations in support of European Union biodiversity laws. And making the data open to all, many hope, will accelerate research—for the benefit of the organisms living in these remote ecosystems, as well as the humans above.

The world of karst, like many fields of study, has been one long marked by research silos, and “biologists are still on one side of the river, with karstologists on

the other bank,” Gregor Aljančič notes. “The result of this project would be that the geologists and biologists will start to work together where this is most needed.”

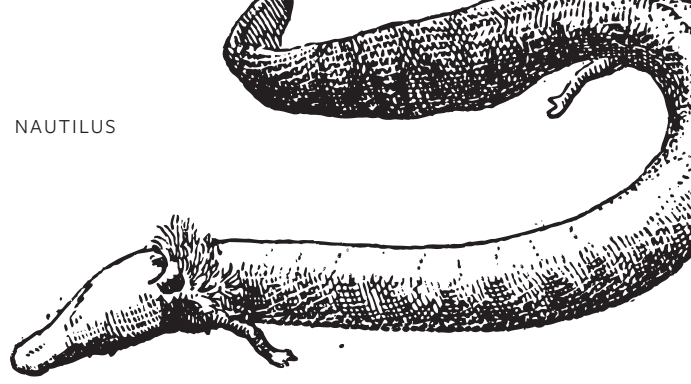
Christos Arvanitidis, CEO of LifeWatch ERIC, a group which aims to use digital technologies to investigate European biodiversity and the ecosystem services it provides, is backing the team's efforts as a new leading example of accessible, multidisciplinary science. “You can show your data to other communities in [a] way they can take advantage of, prove to them that this type of research can be done, and they can perhaps use their own data, for the same kind of analysis,” he says. “That's amazing, because it leads progressively to a kind of knowledge which is produced by as many data, from as many domains, as possible.”

GETTING THE OLM REMOTE STUDY project off the ground would be a huge step forward for cave research more broadly. The field of cave ecology to date has been disproportionately focused on bats, while caves have also often remained outside climate and biodiversity discussions. Organizations working to protect these little-understood ecosystems—and their subterranean denizens—worldwide are watching with interest.

EMERGING INTELLIGENCE

Once thought to be the spawn of dragons, olms still live a mysterious life—one that can stretch for a century. If the Aljančičs' AI-enabled project to study them succeeds, we may learn more secrets about this salamander's extreme biology.





Olms can go for years without eating and have one of the largest animal genomes.

This includes the San Antonio Zoo, whose specialist cave team have set up their own lab, in part geared toward the conservation of the federally protected Texas blind salamander (*Eurycea wallacei*), but also other threatened groundwater species.

“Animals living in aquifers tell you a lot more than spot water checks about the long-term quality of the groundwater,” says Danté Fenolio, who runs the zoo’s Center for Conservation and Research. “Because if some contaminant blew through, there is nowhere else to go; they are exposed to it, whereas sometimes our routine testing misses those contaminants because of timing.”

San Antonio straddles the edge of the artisan zone of the karst-based Edwards Aquifer, where fresh groundwater is easy to tap, supplying 2.5 million people at home, on farms, or in industry. But water flows ever-downward, too. So, notes Fenolio, “There’s a real irony that unfolds, where most of the people that are actively involved in contaminating aquifers live right above them, using those waters, and a lot of folks just don’t think about it.” These threats are varied: nitrates and pesticides from intensive farming, heavy metals from industry, compounds from pharmaceuticals, and petroleum products and other materials from household and

industrial use. And those impacts can wreak havoc on the rare animals adapted to life beneath the surface—as well as trickle back to the water supply for people.

It’s said that some secrets should stay buried. But all signs suggest that leaving those of the olm and other sensitive subterranean creatures in their hidden habitats would be perilous. Whatever happens with the latest effort to better understand the olm’s hidden habitat, its advocates remain steadfast.

“As long as we have this animal, we are obliged to work for it,” says Magdalena Aljančič. Even if their virtual cave lab is never assembled, “it’s not like we’d just concentrate on another species,” she says. “We’ll be motivated to work further, even if that means starting all over.”

And as Gregor Aljančič adds, recalling their days of the 8-bit computer and low-fi video systems, “We are used to improvising, to find all kinds of solutions on the way.” ☺

GARY HARTLEY is a writer and editor based in the U.K. Although his scientific training is in invertebrates, it’s far from his only interest. He likes to seek out underreported aspects of biodiversity, farming, and fisheries.



EXTREME HEAT WILL CHANGE YOU

*High temperatures can alter our
bodies at the molecular level*

BY DIANA KWON





THE HUMAN BODY IS a wonder of adaptations, with clever ways of surviving in even some rather extreme environments. Including fairly extreme heat. Our skin's blood vessels swell to expel excess warmth. Sweat glands release droplets of water that free heat as they evaporate. And deep inside of us, still more machinery is hard at work to keep the body operating smoothly.

But as global temperatures rise and summer heatwaves become the norm in more places, scientists and clinicians are grappling with an insidious and increasingly urgent question: What happens when the cells inside our bodies get too hot—and how does that affect long-term health?

At extreme temperatures, molecules responsible for preventing the harmful effects of heat start to malfunction. Changes also appear at the level of DNA, modifying the genetic material in a way that may be detrimental to health—and possibly even increase the speed at which we age.

“Heat is a very powerful stressor,” says Pope Moseley, a lung and intensive care physician and biomedical sciences researcher at Arizona State University. The evidence Moseley and fellow scientists are gathering suggests that we’re only just beginning to understand the damaging effects of hyperthermia, he adds. “I think we really underestimate heat.”

WHEN THE TEMPERATURE in cells rises beyond normal operating levels, proteins—large molecules whose intricate configurations determine their function—begin to unfold. As heat intensifies, more of these structures become misshapen. If left unchecked, this process can hinder the healthy functioning of a cell and eventually cause it to perish.¹

There are mechanisms in place to prevent cells from meeting this untimely demise. Some of the most important players in this process are heat shock proteins: a set of molecules that were discovered as the result of an experimental error.

It was the early 1960s, and Italian geneticist Ferruccio Ritossa was studying gene expression in the salivary

glands of fruit flies. One day, he noticed something strange. He had been studying chromosome “puffs,” segments of DNA where genetic information is being actively transcribed and translated to synthesize proteins, and an unusual pattern of puffs had appeared. As it turned out, a colleague of his had inadvertently changed the temperature in the incubator where the fruit fly larvae were kept.²

When Ritossa probed this unexpected finding, he discovered that when the fruit fly larvae’s ambient temperature was increased from the usual 77 degrees Fahrenheit to 86 degrees, something changed. In the regions of DNA where the puffs had been observed, the production of RNA, which works as an intermediary molecule between DNA and proteins, appeared to speed up. This puzzling observation, which Ritossa dubbed the “heat shock response,” proved an early clue that there were foundational changes deep inside the body under hotter conditions.

About a decade later, a group at the California Institute of Technology discovered heat shock proteins—the molecules that were the product of this flurry of RNA synthesis.³ Researchers have since learned that heat shock proteins exist in all organisms, from single-celled bacteria to multicellular mammals. Although typically silent, these molecules kick into gear when cells exceed their normal temperatures and help refold unfolded proteins. Heat shock proteins also work in concert with another important cellular process—autophagy, which removes degraded proteins and other cellular debris—to maintain quality control.⁴

But when temperatures get too high, these protective systems may begin to break down.

Heat may also leave marks on our cells at a deeper level: our very DNA.

At the Human and Environmental Physiology Research Unit at the University of Ottawa, adults young and old come to endure high temperatures for uncomfortably long stretches of time. For a recent experiment, participants were invited to sit in a climate-controlled chamber set at 104 degrees Fahrenheit for nine hours. These conditions “gives us a kind of worse-case scenario” of what someone might experience during a heatwave, explains James McCormick, a postdoctoral researcher there.

To examine the effects of these conditions at the cellular level, McCormick and his colleagues studied blood samples taken before and after the heat exposure. They reported that, after the nine hours, immune cells of older adults—those 61 years and older—appeared to be less effective at clearing out damaged proteins (a dysfunctional autophagy response).⁵ This was evidenced by an increase in a molecule called p62, which tags proteins for removal and is destroyed when autophagy occurs. It appeared to accumulate in older adults’ cells, but not in those of younger adults.

The older adults’ cells also showed other changes that weren’t seen in their younger counterparts: There was a reduction in some heat shock proteins, as well

as signs of increased apoptosis—the process through which the body kills off unwanted or malfunctioning cells—and inflammation. These cellular changes may not have immediate effects, but they make people more vulnerable to negative health impacts, such as heat stroke, when exposed to extreme temperatures for multiple days, according to McCormick.

McCormick and his colleagues are now investigating what happens during these lengthier heatwaves: In an ongoing experiment, they’ve asked participants to remain in heat chambers for three consecutive days.

“There are so many different facets of the body, at least at the cellular level, that are affected by heat,” McCormick says. “There are a lot of areas that still need to be explored.”

HEAT MAY ALSO LEAVE MARKS on our cells at a deeper level: our very DNA.

While our foundational genetic code remains relatively stable throughout life, molecules that decorate the long strands of DNA—and play a critical role in determining which genes become activated—are much more malleable. Their architecture can shift throughout a person’s life, influenced by the environment.

The biological changes lingered long after the mercury dropped.

These epigenetic changes can have a broad range of effects, including disease risk and aging—and can even be passed down to future generations.

On one hand, researchers have found that, at least in some animals, epigenetic changes can increase resilience to heat. Scientists have discovered that under certain circumstances—such as when temperatures gradually increase over time—heat can lead to changes that boost the responsiveness of heat shock proteins, enabling animals such as ants, rats, and humans to respond more efficiently to subsequent exposures to heat.⁶

However, when temperatures get too high too fast, problems emerge. Thomas Clanton, a professor of applied physiology and kinesiology at the University of Florida, and his team have observed that mice that have undergone heat stroke—induced through intense exercise at high temperatures—exhibit differences in methylation, the process by which chemicals known as methyl groups are tagged onto DNA sequences, which, in turn, affects how genes are expressed. In 2020, Clanton and colleagues reported that the immune cells of rodents who experienced heat stroke showed different methylation patterns than the animals who had not.⁷ Thirty days after recovering from heat stroke, the animals' cells still showed differences in the expression

of heat shock proteins, showing that the biological changes lingered long after the mercury dropped.

And, when these animals were exposed to endotoxins, molecules found on the outer coatings of bacteria, at the month mark, they mounted weaker immune responses than their counterparts. Which suggests that hyperthermia may lead to dysfunction in the immune system as well. There are hints of this in humans: Some studies have reported that infections are particularly common in people who are hospitalized for heat stroke, suggesting that hyperthermia may lead to immunosuppression, according to Clanton. But more research is still needed, he adds.

Seeing such evidence of heat-related epigenetic changes in mice and other animals, Eun Young Choi, a postdoctoral associate, and Jennifer Ailshire, a professor of gerontology and sociology, both at the University of Southern California, set out to examine whether extreme temperatures may also affect the human epigenome.

In a study published earlier this year, the duo reported that, after analyzing blood samples from more than 3,600 adults over the age of 56 across the United States, those who had experienced long-term exposures to extreme temperatures showed epigenetic changes indicative of accelerated aging.⁸

Aging leads to changes in DNA methylation, and scientists have used these patterns to develop so-called “epigenetic clocks” that can predict a person’s disease risk and lifespan. Residents of places with 140 or more days of temperatures exceeding 90 degrees Fahrenheit per year experienced more than a year of additional biological aging compared to those living in places with fewer than 10 days of that sort of heat. These differences persisted even after taking into account other factors, such as socioeconomic status, physical activity, and smoking and alcohol use.

How these signs of molecular aging link to specific health outcomes remains to be seen—but these results are in line with other studies that have linked higher temperatures to more rapid aging at the molecular level.

“The key message from our findings is that heat could be affecting healthy populations in ways that we can’t see,” Choi says. On levels that remain hidden.

MANY UNANSWERED QUESTIONS REMAIN when it comes to the molecular effects of heat stress in the human body. But researchers hope that the knowledge being accumulated will lead to new interventions that help improve heat resilience as our world warms.

Studies show, for example, that there are ways to increase heat tolerance. One method is through exercise. During heat stroke, the reduction in blood flow to the gut can cause the intestinal wall to become leaky, allowing endotoxins to leak out into the blood stream, triggering an immune response that can turn deadly. Moseley and his colleagues have found that exercising in reasonable heat—safely and for limited periods—activates the release of heat shock proteins and can tighten the lining of the gut, lessening these harmful impacts of extreme heat.⁹ But physical exertion during heatwaves can be dangerous, Moseley says. “If you’re in Phoenix and you decide you want to exercise, but it’s 105 degrees outside, that’s not a good idea.” The line can be fine between heat-training and overheating.

Researchers are also exploring whether there might be drugs that can stimulate cells’ protective mechanisms against heat. This is very much in its infancy, because scientists are still trying to better understand what happens to cellular processes under extreme conditions, McCormick says. “Everyone’s looking for some

kind of breakthrough to try to protect people.” Especially as summers continue to grow hotter.

While interventions to improve heat resilience at the individual level—as well as efforts to build better, safer infrastructure—might someday help keep people cool during heatwaves, these biological and built solutions have their limits. To circumvent the worst outcomes for our warming planet, humans will ultimately need to address the causes of warming, rather than just its consequences, Moseley says. We’re trying to adapt our way out of extreme heat, he adds. “But we can’t.” ☺

DIANA KWON is a Berlin-based science journalist who covers health and the life sciences. Her work has appeared in *Scientific American*, *Nature*, and *The Scientist*, among other publications.

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With Regard to the Invisible

The climates that run through us

BY A. KENDRA GREENE

ILLUSTRATIONS BY THE AUTHOR

I understand that which is not visible, for example; heat, weight, pleasure, etc.

There is the visible that is seen ... and the visible that is hidden ...

—René Magritte

IT'S LATE. I SHOULD be telling my nieces a bedtime story. But instead I accept their invitation and step outside into the windstorm that has had us wondering all day what the High Wind Warning really means. Their parents and I can't remember having seen one before, don't exactly know what to do. It's January in Burbank, California. Earlier in the day I was headphones-on, sensitive to so much as a stomach gurgle, recording an audiobook when my engineer got a text from a studio a few miles away warning us to "save often," that they had already lost power and with it all the work that day, the record evaporated and the words like they had never been spoken. Nothing happened to us. Nothing except all the tree branches I saw in the street when I walked over that morning, one impaled through the windshield of a parked car, perfectly vertical, like it had sprouted from the dash.

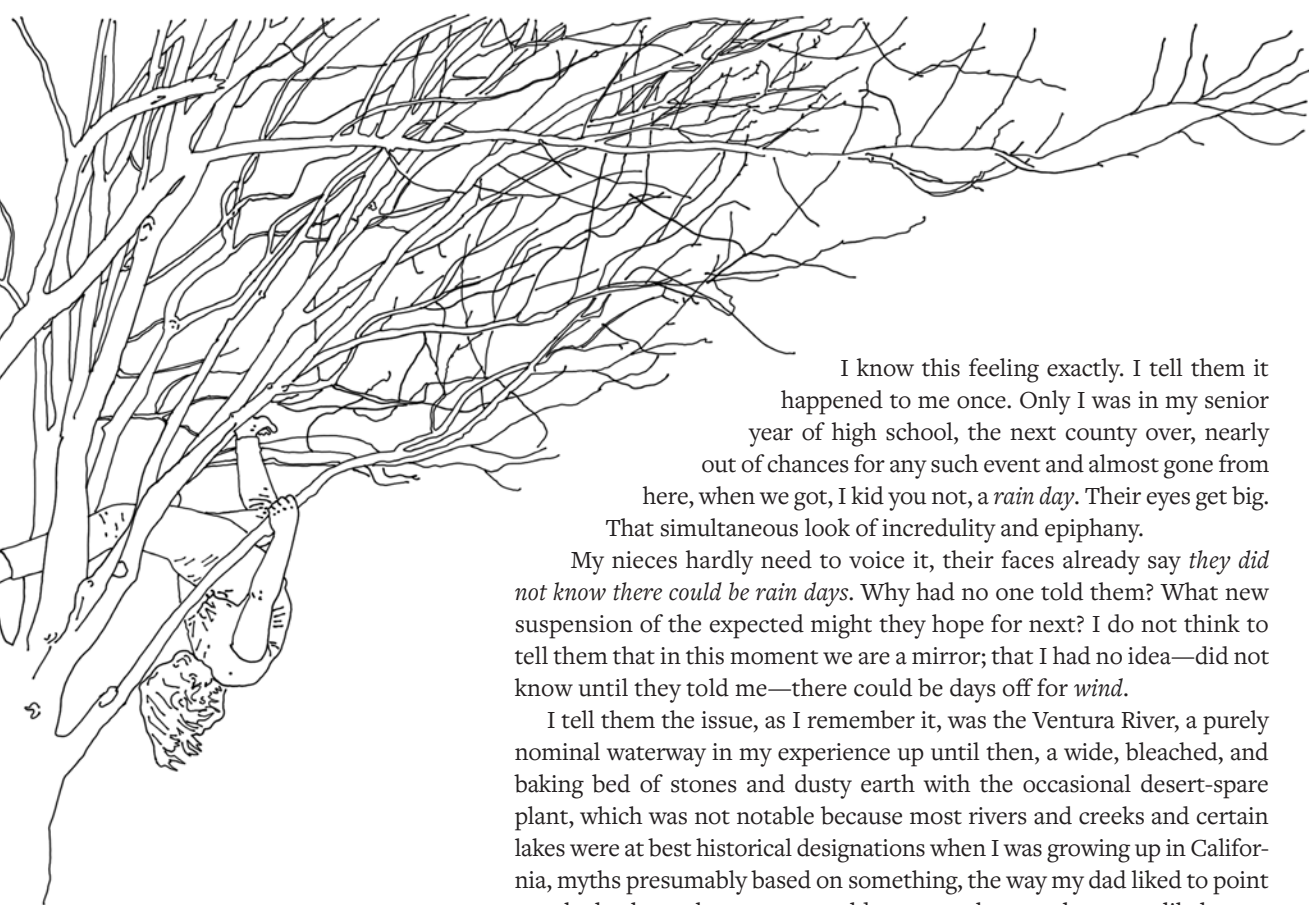


It is not enough for my nieces to stand out in the wind, feel its force push us and whip our hair. No, we must run. With it, through it, against it. As though the wind would lift us up. As though it might knock us flat. We chase after each other, after the wind itself, gust by gust learn its currents and waves and walls. It is wind enough, already flecked with debris bigger and faster and traveling more horizontally than a standard gale, that I am glad two of us are wearing glasses, have that much shield in the dark. We run, in delirious circles, arms airplane out, looping in near misses at one another. We pick up as much speed as we can without leaving the front yard lawn, the thrill of almost collision, almost disaster, almost connection still a dizzying kind of play.

We have already taken down the wind chimes. And some spinning baubles left over in the plum and crape myrtle from the holidays, the girls happy to climb up for the high ones. We have tried to imagine what can

be blown down, blown away, blown into something else and smashed. That was while it was still light out, our sense of caution still tentative, an act of imagination, a faith that the people who knew about these things had chosen to sound the alarm, and we should probably do something.

The next morning school is canceled. My nieces are thrilled. They rush toward me in the hallway, no time to waste, joy that cannot be contained. Alice is 12, almost tall enough that her glowing face is even with mine. Corinne is recently 8, has a grin full of baby teeth and adult teeth and scalloped gum gaps in between, still at a stature to beam up at me. They tell me how *other kids* get snow days. How they thought they'd never get one. How *unfair* it is, to be deprived like that. But now they have one! Miraculously! They radiate vindication. I see nothing short of justice shine through them.



They tell me how
other kids get
snow days. How
unfair it is, to be
deprived like that.

I know this feeling exactly. I tell them it happened to me once. Only I was in my senior year of high school, the next county over, nearly out of chances for any such event and almost gone from here, when we got, I kid you not, a *rain day*. Their eyes get big. That simultaneous look of incredulity and epiphany.

My nieces hardly need to voice it, their faces already say *they did not know there could be rain days*. Why had no one told them? What new suspension of the expected might they hope for next? I do not think to tell them that in this moment we are a mirror; that I had no idea—did not know until they told me—there could be days off for *wind*.

I tell them the issue, as I remember it, was the Ventura River, a purely nominal waterway in my experience up until then, a wide, bleached, and baking bed of stones and dusty earth with the occasional desert-spore plant, which was not notable because most rivers and creeks and certain lakes were at best historical designations when I was growing up in California, myths presumably based on something, the way my dad liked to point out the back way home was an old stagecoach route, but most likely now only figurative or approximate or aspirational, honorifics like the Colonel in Colonel Sanders. You said “river” and it was a mark of respect or affection, a nod to the presumed wisdom of your elders, as much folklore, as much tradition as anything else.

But of course the water, when it finally came, remembered, and not only was there water in the creek, jumped its banks and rising up to the pasture now a marsh, water in the rivers sweeping brush and river rocks and rattlesnakes out to sea, there was so much water rushing down the gutters you couldn’t see that they were there. There were low water crossings that finally had any water at all, so much water that it got dangerous for the school buses to pass, and so they just closed school and waited for the deluge to clear.

I stayed home with my mother, who maybe could not get to work or maybe her district felt the same distress, and we listened to the rain against the roof, watched the roads become rivers of their own, ate carrot sticks and tuna fish sandwiches and made hot chocolate because that is what we did on rainy days, because that’s what her mother used to do for her. We fell back on old rituals in the face of this unprecedented thing.

I realize I don’t know if we’ve ever really told the nieces about the drought their father and I grew up in, that I knew the word drought (and that we were in one) since forever, that I was younger than Corinne’s age when it started and nearly Alice’s when it ended, in torrents of rain, some months after it was predicted to last a nearly unprecedented seventh year, a thing that hadn’t happened since the 1500s.



POOL DREAMS

In 1955, my grandparents had a swimming pool built in their Pacific Palisades backyard. The house was demolished 50 years later, but the new owners kept the pool.

Indeed, I don't know what they know about it. If they know about it. How you could get a glass of water in the lucky event of a trip to the Spaghetti Company, but you had to ask for it, a little card with a camel on it reminding you about the drought as you slid into the booth. How it sounded like a competition, like breaking the four-minute mile or the sound barrier or the Earth's gravitational pull, but was also a mark of virtue to take a shower in three minutes or less. How pools went unfilled. How low-flow toilets became a thing people who wouldn't otherwise talk about toilets suddenly couldn't stop talking about. How the lawns that went dead were dug up or paved over or spray-painted back to green.

A few years before I had nieces at all, I remember thinking that I felt a shift coming, a kind of tipping point, that already, even in terms of technology, so much had changed so fast that there was about to be too much to explain to someone new to all of it, a child or an alien, and I meant just the part I'd lived through. Even just that, a few decades, was about to be impossible, all of it still recent memory, but simply too much.

If I attempted neither that vast subject of computers or the niche history of beepers, didn't get into AOL or ICQ or Napster or Friendster, skipped right over the first Nintendo and The Real Talking Moose, ignored the era when microwaves were new enough to us that my sister the

We worried the way one does as *watch* turns to *warning* to *you have to get out.*

mathematician had the default belief everything went in for three minutes; if I just tried to follow one thread within my own lived experience, it was, even then, nearly too much to communicate the nuance of rotary dial and call-waiting and cordless phones and answering machines and the cliff of minutes per month I could talk on the cell phone, which was my only phone, how I would call my brother at the stroke of 8 pm because then the call was free.

I mean, my parents grew up with party lines, operators, phone numbers that started with letters, and I'm not even touching that, not getting into that because, already, just within the borders of my half-lived life, it is too much to convey to the uninitiated, too much information about how we've kept iterating our attempts to share information.

The seasons of my youth ran on two calendars. There was the largely ceremonial observation of Fall, Winter, Spring, and Summer, most apparent in the decorative borders of elementary school bulletin boards. And then there was the more local, even familial version that cycled through the fresh mowed scent of Weed Abatement, the marine layer beach days of June Gloom, the crisp dry heat of Santa Ana winds, my father at the nursery crowing Bare Root Season as if the spindly stick saplings in his grip were already leafed out in stone fruit. Fire Season was a thing. We've always known people with stories about hosing down their roofs, about the house next door, about it could have gone the other way. But it used to flag a risk more than a certainty.

I was traveling with my parents in 2017 when the Thomas Fire started in Ventura County. My parents went back home, even as neighbors had to flee, home to what became the largest wildfire in California history, which held the title a few months before another, and another claimed it in less than a year. One of the handful of phone numbers I still know by heart goes to the childhood home of my childhood best friend. Her parents evacuated the first night as the fire came over the hill. I don't know what that phone number calls anymore.

My high school friends fell into a kind of virtual reunion that week, everyone texting to check on each other's parents, watching the maps, seeing if the sites of our sleepovers and birthday parties and study sessions and movie nights stayed standing. We worried the way one does at a distance, the way one does having read the reports, the way one does as *watch* turns to *warning* turns to *you have to get out.*

Don't worry, my father said when I called, the dividing line is Main Street but you only have to vacate *north* of Main Street; which meant the convenience store across the street where my brother and I spent the money we made on Nerds and Lemonheads, well you can't go there, but the old bungalow with the shag carpeting that's still our dad's office is on the *south* side of Main Street so, by his reckoning, when I call, it's fine. Technically, he can still park out front, will probably go in for a few hours later today, but anyway, he's home when I call, out by the oak tree. I

say I hear there's a warning there, too, ask how it's going. It's fine, my father insists, it's fine. But honey I'm going to have to call you back, he says, there's a firefighter here who wants to talk to me.

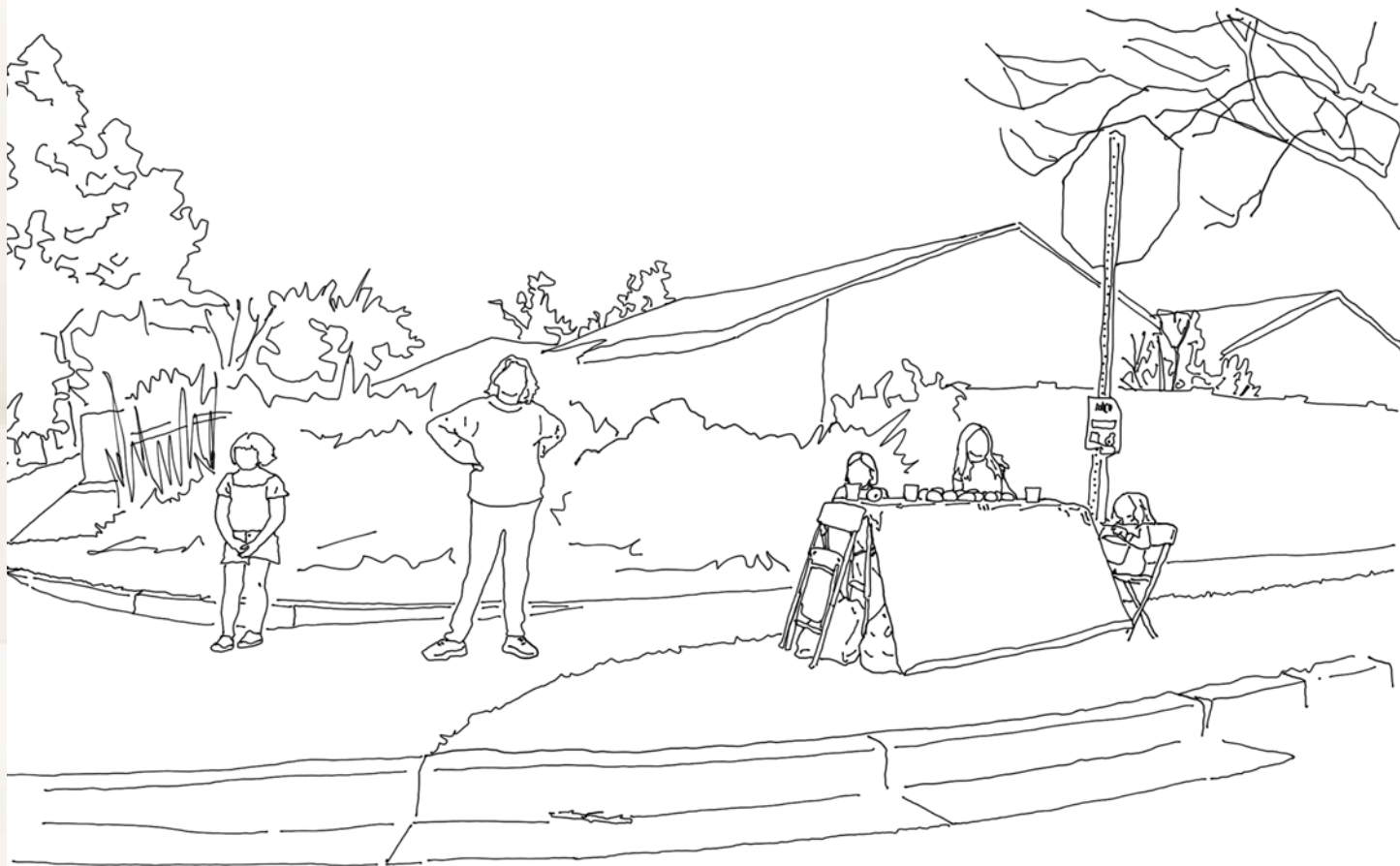
When I tell this story, I tell it as a story about my father, a character study of this one stoic, obstreperous, unfathomable man. But it's a story about what we get used to, too. About fire and place. About weighing risk. About what starts to become inevitable. About what has always been invisible. About denial, I guess, about witness and observation and forgetting and untold. About how a third-generation Angelino talks to his daughter about the land she was raised on, how I tell his granddaughters about that.

My grandparents lived in the Pacific Palisades, a corner lot with a drooping trunk pepper tree dipping over the front walk that, even as a kid, I had to duck under. One side of the house was fenced in and

I've since come to think of guilty pleasure only when I think about terrible beauty.

lined with recycling bins, a squad of squat, sturdy, color-coded tubs that siloed newspaper and tin cans and each precise particular material they would take, and the other side home to a kumquat tree. There was a prodigious tangerine tree in the back, leaves past the roofline. My dad and his sisters say the fruit was fine when the tree was planted, but slowly got worse and worse, which is maybe why when my sister was a kid it was expendable.

My dad, there in his childhood backyard, showed her, his then only offspring, how you could breach the citrus skin at its navel, reveal a cavity at the tangerine's empty core just right for cradling a firecracker, swaddled so snug you could light the fuse and chuck the orange bomb at your loved one, feel the blunt bumper thud of it against your body or, better yet, the whole thing burst in midair, spectacular, rind and pulp and peel on your skin and in your hair and sticky blast stuck to everything.





Firecracker fights were family lore by the time I have memories, almost unbelievable, like the goats I tell my nieces about that get hired out for weed abatement: four-footed no-collar employees who gnaw down the kind of hillside where it's too steep to mow, those vast blonde slopes that meet the freeways, for instance, but also at places like Angel's Landing, the funicular right in the middle of downtown. I tell them because it's a fun story. Whimsical. Surprising. The goats are compelling characters even before they get jobs and show up where you least expect. I tell them because the goats are so clever, so skilled, so well-equipped and so sure on their feet as they navigate so much of this Earth, wrap their tongues around what will sustain them, bring

their teeth down on stalks and stems and blades, tear up what they need, and unroot the world.

I tell my aunt in Utah and she says goats! They can eat tin cans and the laundry off your line and somehow get something out of it. I tell my nieces about the clotheslines I've seen in Iceland, sheets blown out straight. I tell them about friends who honeymooned there and had a car door so wrenched bent by the wind as they opened it that they drove halfway around the island unable to shut it again. I tell them about a place on the southern coast where I summited a series of steep switchbacks and popped up on the flat plateau of a mountain, a largely vertical approach to an edge that yielded the very horizontal, a vast lake feeding the waterfall I'd passed on the



HELD CLOSE In 1966, my grandmother, in front of her Palisades home, holds her granddaughter, 11 months old, as her own arm was held by her visiting mother-in-law, my Los Angeles-born great-grandmother.

cliff face and a wind so fierce it held you up. I'd never known anything like it: those surges and pulses, the sheer force of it. It was fearsome, to be buffeted like that. And yet I could lean in and be held. Indeed, once I got the hang of it, trusted some part of the constant bluster—even as I wondered how I would ever get back down—I bent my knees and sat in it like a chair.

It won't just be *the* wind day, the teachers in Burbank pushing all the desks in their empty classrooms away from windows that could be broken when the eucalyptus fall. The schools will stay closed three days, the rest of the week. The facts of the fires will grow ever more devastating. My mother will text the family thread as our grandparents' old address in the Palisades is swallowed by the fire map.

I try to explain to the friends across the country that ask, I haven't even had grandparents for 20 years,

that the house they bought when my dad was 3, where they kept a jar of maraschino cherries in the fridge to make Shirley Temples, where they celebrated their 50th wedding anniversary surrounded by all of us around the table and I first encountered those plastic champagne coupes you twist together so the stem joins the base—so fancy, so satisfying to assemble and take apart and put back together again—that house was demolished years ago by a different force, torn down almost the moment it was sold so something bigger could take its place. I tell my friends the nieces are fine, that six miles sounds closer than it is. I tell them a friend could finally take her mother back to where her house had been and there was just the front steps and the fireplace. I try to explain that it's nothing, it's absolutely nothing, but I wonder about the kumquat tree.

**HAND-ME-UP**

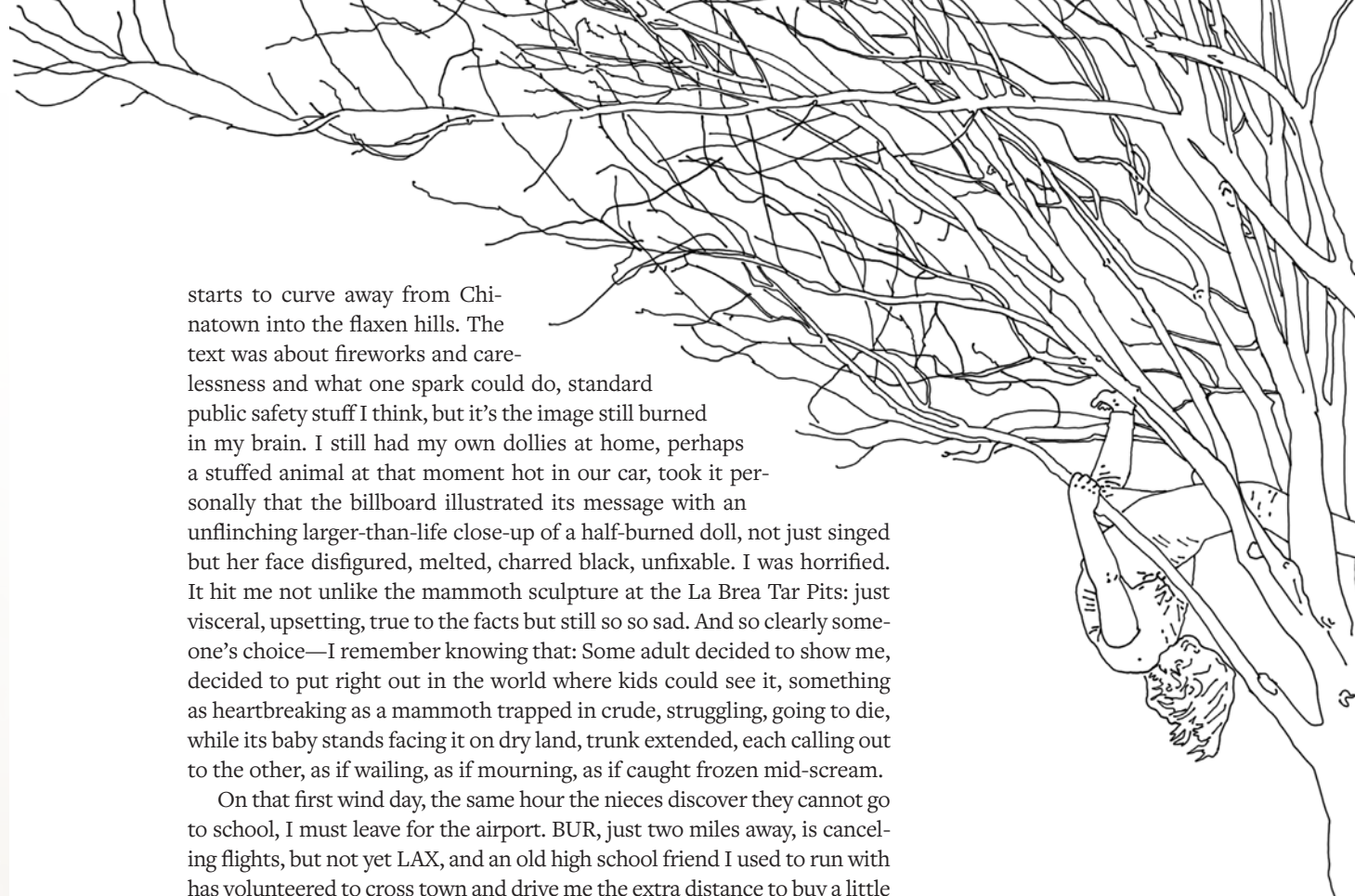
Great-grandfather on a visit to the Palisades home in 1966, with his son wearing the Pali High class sweater of his own son (my father), in the class colors of beige and seal brown.

I don't know, don't think to ask until now, how many times in all those decades my grandfather listened to the radio and had the car packed just in case. I forget that my dad, and the rest of Palisades High, was evacuated to University High during the Bel Air Fire, and in the official phone calls to tell all the parents no one called his, so he walked home. But we didn't miss school, my father says, says as though evacuation doesn't count, which maybe it doesn't because this has always, somehow, been a story not about fire but about that walk. So much depends on the story, on who tells what and if any of it pieces together. Only once I ask my dad about his first memories of the Palisades house, nearly his first memories at all, do I hear how my grandfather gave him a toy fire truck, the kind you could pedal yourself, I assume while wailing like a siren, as soon as they moved in.

By the weekend, my nieces go over to their cousins' and the lot of them pick up the carpet of avocados blown down from a three-story tree in the backyard. There are branches on the ground, a thousand avocados easy, the leaves just shredded on the side of the tree facing the wind and the other side basically fine. The five cousins set up a little avocado stand on the corner, a tiny sidewalk charity, sit there in the sun, raising money for people displaced by the fires, at least one such family they know. Corinne flags down potential customers on the bike path. One person makes a hefty donation. Others can't keep from haggling, as if it were possible to come down from the stated pay-what-you-wish. Those fires will burn for three more weeks.

There was a billboard I saw in L.A. as a child, in the glare of summer sun between dim sum at The Golden Dragon and our car parked a little way up, as the road

COURTESY OF A. KENDRA GREENE



starts to curve away from Chinatown into the flaxen hills. The text was about fireworks and carelessness and what one spark could do, standard public safety stuff I think, but it's the image still burned in my brain. I still had my own dollies at home, perhaps a stuffed animal at that moment hot in our car, took it personally that the billboard illustrated its message with an unflinching larger-than-life close-up of a half-burned doll, not just singed but her face disfigured, melted, charred black, unfixable. I was horrified. It hit me not unlike the mammoth sculpture at the La Brea Tar Pits: just visceral, upsetting, true to the facts but still so so sad. And so clearly someone's choice—I remember knowing that: Some adult decided to show me, decided to put right out in the world where kids could see it, something as heartbreaking as a mammoth trapped in crude, struggling, going to die, while its baby stands facing it on dry land, trunk extended, each calling out to the other, as if wailing, as if mourning, as if caught frozen mid-scream.

On that first wind day, the same hour the nieces discover they cannot go to school, I must leave for the airport. BUR, just two miles away, is canceling flights, but not yet LAX, and an old high school friend I used to run with has volunteered to cross town and drive me the extra distance to buy a little more time together before I go. Her kindergartner is still in class, won't have the thrill my nieces do until the next week, if indeed he is yet accustomed enough to the routine of school to appreciate its unanticipated disruption.

The wall of clouds seen from the front yard lawn, what must be smoke as much as clouds but is still blue in the morning light, just vertical and towering, is so striking, so awesome, so nothing I can remember having seen. The light is wrong for the time of day, off but so beautiful, in a way that reminds me of when I've stood under the totality of a solar eclipse. I try to recall the cloudscape painted up cathedral vaults, maybe great canvases in museums, some document I would have until that moment interpreted only as art. But all I can think of are the Magritte paintings, which, come to think of it, I first saw in Los Angeles, a field trip the winter of my senior year, the silhouette of trees and town in evening lamplight, the sky filled with clouds and blue as day.

Just in an exit or two the freeway takes us toward flames, toward smoke that is fresh and dark and rolling, low. The views looking left or right from the car are wholly divorced, different color and light, increasingly night and day. There is a spot of orange, tinged in pink, the right size and place to be flames cresting the ridge or the sun rising over the mountains, except there's too much blue gray purple brown haze to see



Your wildfires they kept saying, as though I had flown in and brought flames along in my luggage.

the mountains and I'm unsure if I'm right either way, though I stare, watch for some telltale ripple or ebb.

A few more miles and the atmosphere turns golden, rays diffuse and refracted, a sepia glow. By time we are moving past downtown L.A., it does not matter that the windows are up. A headache is starting. I feel the change of the air in my lungs. The diminishing. The tightening. The hurt. The light outside is stunning, though, gorgeous, the way an ice storm is a kind of guilty pleasure—so beautiful and so terrible, so patently disaster or the precipice before.

I have a feeling there in the passenger seat that is definitely not nostalgia, nothing I would ask to return to or anyone else to know, yet still a kind of recognition, a restoration, a knowledge that is stored in my body, lodged there and now triggered with the gap closed immediacy of time travel. It is not a comfort, exactly. I find it neither bitter nor sweet. But I am rooted in sudden access to the fact I have felt this, I have known this, this has happened before.

Back when I had an iPod and a long commute into downtown Chicago, I started a playlist titled "Guilty Pleasures." I didn't get very far with it, realized I didn't actually feel guilty about how I feel about Neil Diamond or Britney Spears, and retired the phrase as not useful. I've since come to think of guilty pleasure only when I think about terrible beauty; that's what resonates, how exquisitely an ice storm sets the visible world: glossy, encased, defined, nothing more beautiful than the sunlight coming through a frozen branch of frozen berries. Everything gilded, but in diamond not gold. And sonically, too, otherworldly: It is the silence of industry ground to a halt but everything else stopped, too, every insect and rodent and bird—frozen, as we say—that pin-drop clarity of utter stillness, of nothing kinetic, of energy all potential, breath held, heart all but stopped. That simultaneous stopped and anything could happen next. Then, occasionally, the tinkle of glass leaves, the bow-drawn groan of limbs straining to move, the squeak saw crack of branches burdened, then breaking, suddenly sheared under the weight and crashing down, that occasional punctuation, set off by the smallest breeze.

My aunt in Utah says she's been thinking about the colors, the textures, the what you get when things that aren't supposed to burn go through all that heat and chemical shift. It must be stunning, she supposes. Stuff you never get to see. Freon and neon and heavy metals,



PEPPER TREE TRAPEZE My father knotted a bamboo and clothesline rope ladder for his firstborn (my sister), installed in his childhood front yard in the Palisades and repurposed a little later, in 1974 as a trapeze.

Your wildfires the folks in Salt Lake kept saying, as though I had flown in and brought flames along in my luggage. As though the fires were my children, in need of supervision. As though the responsibility of what burns to the ground and what the wind carries on the air belonged quite possibly to me and me alone. They made a point of it: *your wildfires*. And though I heard the distance it implied, the disapproval, the edge, the fault, the washing their hands of it, it pleased me when they said it, that that they still marked me as a Californian, like my nieces, like my great-grandmother, had not consigned me merely to my mailing address, to where I live

the whole industrial chemistry set tucked away in our appliances and back sheds and commerce. She wants to know the experience of living in these colors, of literally breathing them in. But she's careful who she mentions this fascination to. She doesn't want to sound heartless. She doesn't want to sound like she doesn't understand, like she doesn't see this for what it is.

It was last summer I first noticed the people I knew in Salt Lake talking about wildfires in the tongue of my West Coast childhood. It happened with locals and transplants alike, in canyons and coffee shops, at a friend's house in the hills looking across the sweep of the valley. Not only the language, the fact of air quality and containment and evacuation route and how much longer can we stay, but something in the tone, what I can only name a familiarity, the sound of understanding.

in Texas and the panoply of crises there. I have lived somewhere else most of my life now, and it pleased me to think that they saw me as Californian, indelibly, roots laid bare, regardless of the seasons by which I am blown elsewhere. They're not wrong. I accept my inheritance. Though surely what I should have thought, what I should have known, is: *They're our wildfires now.* ☺

A. KENDRA GREENE is the author and illustrator of *No Less Strange or Wonderful: Essays in Curiosity* and *The Museum of Whales You Will Never See*. A writer and book artist, her work is also published in *Atlas Obscura*, *The Guardian*, *Orion*, and *The Wall Street Journal*. It has come into being with fellowships from Fulbright, MacDowell, Dobie Paisano, UNC special collections, Library Innovation Lab at Harvard, and The American Library in Paris.



You Want Extreme Weather? Visit These Seven Planets

*An intergalactic tour of the most terrifying and
beautiful climates in the universe*

BY CLAIRE CAMERON

IMAGES COURTESY OF NASA/JPL-CALTECH

A

MONG THE MANY JOYS of traveling, escaping the norm is a top draw. On Earth, that's a little harder than you might think. Our planet's various climates may seem distinct, but they are mundane compared to what else is out there. We must go farther afield—and I mean really farther—to experience something truly strange.

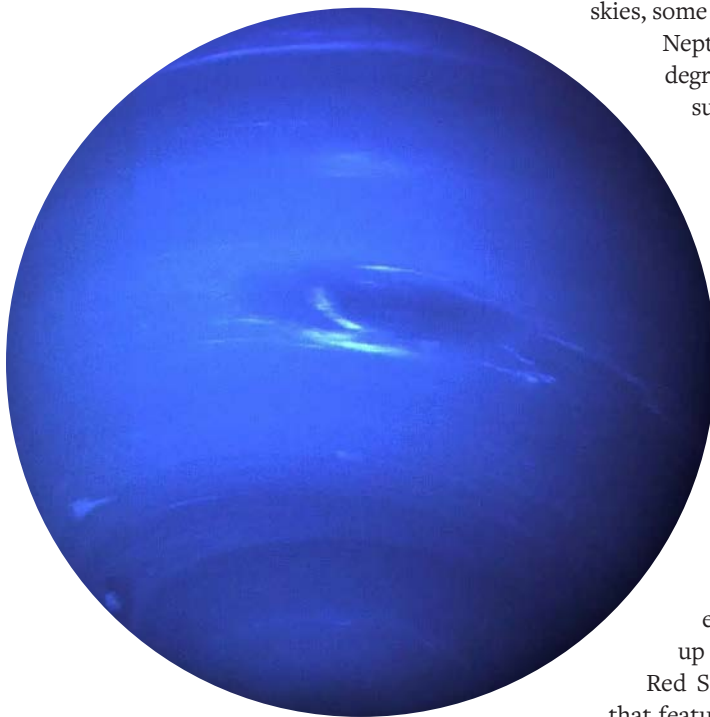
With science as our guide, let's visit alien worlds with some of the most extreme, terrifying, beautiful, and bizarre climates in the known universe. Our itinerary includes seven stops. We begin in our solar system.

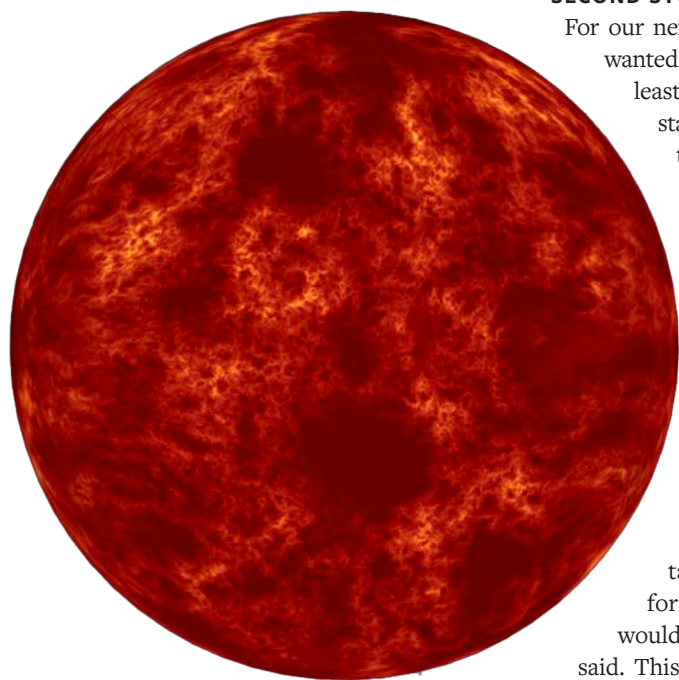
FIRST STOP: NEPTUNE

On Neptune, we hope you can withstand freezing temperatures and bone-crushing pressure. Prepare for pale turquoise skies, some clouds, and a chance of diamond rain.

Neptune's upper atmosphere is a chilling -396 degrees Fahrenheit. As you descend toward the surface, you'll encounter clouds of methane and other hydrocarbons, which liquify the farther you go. As the light fades, the pressure and the heat build. When the temperature reaches that of Earth, the methane might start to fall apart, its carbon atoms reforming as diamonds, which would fall toward the planet's core. Oh, and then there's the wind.

Neptune's winds are the strongest in the solar system—over 1,200 miles per hour, far beyond the speed of sound. Why is a mystery. On other planets with such supersonic winds, their star's energy drives the gale, but Neptune is too far from the sun for this explanation. Such intense winds can whip up terrible storms, yet unlike Jupiter's Great Red Spot, a hundreds-of-years-old anticyclone that features winds up to 400 miles per hour, Neptune's storms don't seem to last so interminably, so at least there's that.





It rains
molten
glass,
sideways.

SECOND STOP: 55 CANCRI E

For our next stop, we're bringing the heat. If you've ever wanted to visit an active volcano, 55 Cancri e is for you. At least half of its surface is lava. A lack of somewhere to stand, however, is a trifling inconvenience compared to the certainty of being vaporized.

Located some 41 light-years away, 55 Cancri e is very close to its star—a year lasts less than two Earth days—and tidally locked, much like our moon: Trapped in sunlight, the dayside is about 3,500 degrees Fahrenheit, or “hot enough to melt all types of known rock,” explained Michael Zhang, a postdoctoral fellow at the University of Chicago. The lava is so hot that it would not appear red, as we might imagine on Earth, but would instead glow bright, pale yellow.

55 Cancri e is too near its star to have sustained whatever atmosphere it had when it first formed. But somehow, it has one—55 Cancri e would likely be hotter if it didn't have *something*, Zhang said. This secondary atmosphere is thought to be composed of carbon monoxide and carbon dioxide, created by gases arising from the lava ocean in a constant cycle of creation and annihilation. Shiny clouds, likely made of silicates, could also reflect away some of the star's heat.

The nightside offers little relief: It is far hotter than Earth, at about 2,509 degrees Fahrenheit. Most rock melts between 1,100 and 2,500 degrees Fahrenheit, so you're probably still going to have a lava ocean—albeit a cooler one, with an orange tinge. The day-to-night difference is great enough that some of those clouds might even condense. The nightside is also dark, so you're less likely to spot any reformed rocks that might fall on you from those clouds, like being pelted with gravel.

THIRD STOP: TRES-2 B

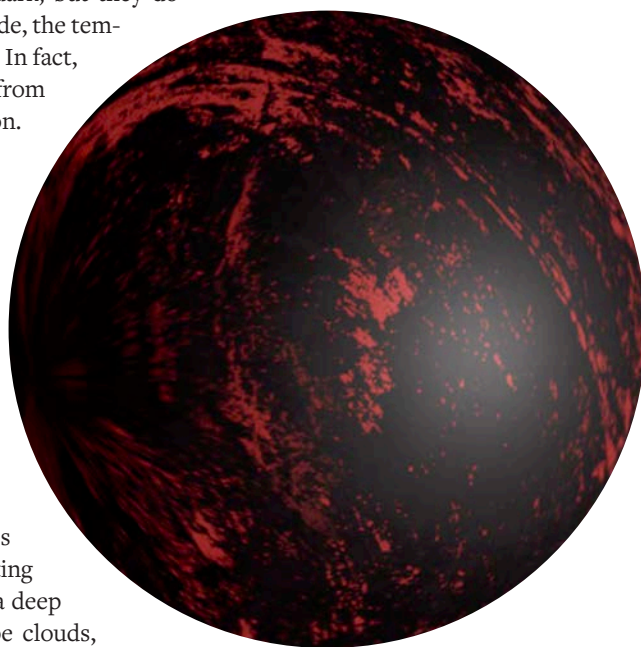
Our third destination is one for the goths: TrES-2 b holds the honor of being the darkest exoplanet ever found orbiting a star.

This gas giant absorbs almost all the light that hits it, reflecting barely anything back into space. For comparison's sake, coal—the least reflective naturally occurring material on Earth—absorbs 95 percent of light. TrES-2 b absorbs 99.9 percent, making it darker than black acrylic paint, but not quite as absorbent as more exotic substances, like Vantablack.

Scientists don't know why this world is so dark, but they do know that TrES-2 b is very, very hot—on its dayside, the temperatures reach around 3,140 degrees Fahrenheit. In fact, the only light scientists have observed coming from the planet seems to be entirely thermal emission. “If you're in a spaceship flying by, it wouldn't be invisible, even though it's the darkest world,” said David Kipping, an astronomer at Columbia University. “It's just glowing like an iron being pulled out of the fire.”

How bright is it? Well, if TrES-2 b were in our solar system, then it would be thousands of times brighter than Venus. That's partially because TrES-2 b is huge compared to our shiniest neighbor, with a mass of about 1.5 Jupiters.

Cross over to the night side, however, and the temperature drops significantly. Out of the star's glare, it's cool enough that much of the heat radiating from the planet would no longer be visible, but a deep crimson glow may remain. There might even be clouds, although what kind is a mystery.



FOURTH STOP: KELT-9 B

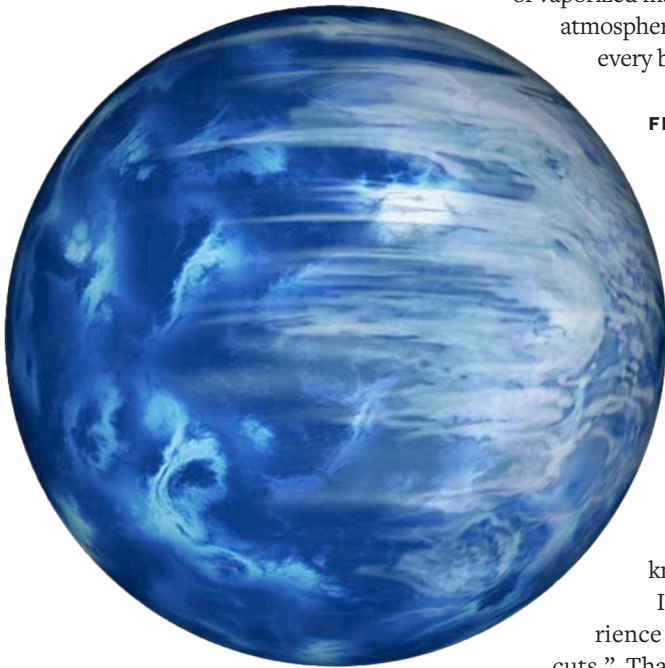
At this point, you thought you knew hot. But you didn't know KELT-9 b. A super-Jupiter, the planet is tidally locked to its star and has the odd distinction of orbiting perpendicularly.

On its dayside, the planet clocks in at about 7,800 degrees Fahrenheit, almost as hot as the surface of our sun, and hotter than many other stars found in our galaxy. And because it is so close to its host, it is bathed in radiation. If you have ever wondered what it feels like to be on a star, then KELT-9 b is your opportunity.

Unfortunately, you won't feel anything for long, because KELT-9 b is so hot that scientists believe molecules there are being ripped apart into their constituent atoms. At least some of the dayside's heat is transferred to the nightside, so there must be some wind, which likely pushes those atoms over, too. There they might reform, temporarily becoming molecules once more ... only to be torn up again.



In fact, the planet appears to be tearing itself apart. Scientists believe that as KELT-9 b zooms around its star—its orbit lasts about 2 and a half Earth-days—it’s disintegrating, evaporating so fast that it might even have a tail of vaporized matter, like a comet. According to one estimate, its atmosphere loses the equivalent of 18 to 68 Earths in mass every billion years, so be sure to visit before it is gone.



FIFTH STOP: HD 189733 B

From a distance, HD 189733 b could be mistaken for our own planet. As you approach, it would appear uncannily like Voyager’s famous “Pale Blue Dot” image of Earth—a cobalt-colored ball, suspended in the void.

A gassy planet a bit bigger than Jupiter, HD 189733 b is blue, hot, and extremely windy. Its winds howl at up to 5,400 miles an hour, seven times the speed of sound and far beyond anything in our solar system.

Indeed, this world’s violent storms, diminishing atmosphere, and turbulent winds make it among the most hostile to life (as we know it) worlds that we have ever discovered.

If you’re caught in this maelstrom, you’ll experience what NASA has called a “death by a thousand cuts.” That’s because it rains molten glass, sideways.

Silicates in the atmosphere on the dayside will be blown by the winds to the nightside, a transition that comes with a 500-degrees-Fahrenheit temperature drop, enough for them to condense into small droplets that, because of the wind, wouldn’t so much fall as fling. You might compare the experience to standing inside a world-sized blowtorch, wind tunnel, and sandblaster all at the same time.

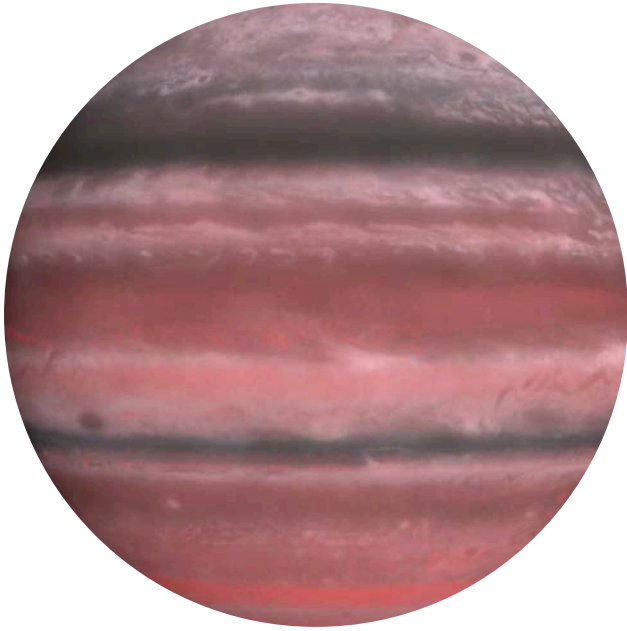
To make matters worse, HD 189733 b appears to have hydrogen sulfide in its atmosphere, which means it would reek: On Earth, this colorless gas causes the rotten egg smell that you may have had the misfortune to sniff while walking by an open sewer.

SIXTH STOP: GJ 9827 D

By now, you’re likely craving a bath, if for no reason other than to scrub away the stench of a Jupiter-sized landfill. GJ 9827 d can do you one better: Perhaps among the most bizarre planets yet discovered, this world is composed almost entirely of water.

Water vapor, to be exact. The planet is estimated to be about 450 degrees Fahrenheit, or around the same temperature as the surface of Venus, and has a possible rocky interior enveloped in a thick, watery atmosphere. This complex, heavy atmospheric makeup is similar to rocky planets in our solar system.

The
planet
appears to
be tearing
itself
apart.



It's a tantalizing idea: Water is a key ingredient for life. Yet this so-called "steam world" is believed to be too warm to be hospitable to life as we know it. But what about that which we don't know? GJ 9827 d's very existence suggests there may be other water-laden worlds, opening a new avenue for astrobiologists in search of extraterrestrial life.

FINAL DESTINATION: WASP-76 B

We end this tour in a blaze of glory.

Very similar in mass to Jupiter, gas giant WASP-76 b is another world that exists very close to its star, meaning it, too, is incredibly hot.

Hot enough to vaporize lead and iron on its dayside, which always faces its star. WASP-76 b's blasting winds likely whip that metal vapor round onto its nightside, where they might condense and fall as iron rain.

What it lacks in habitableness, the planet may make up for in beauty. Astronomers believe WASP-76 b's atmosphere may produce a "glory" effect, which is essentially a trick of the light that looks something akin to a Medieval saint's halo made of rainbows.

Although it appears almost like a circular rainbow, a glory is very much its own thing and requires very distinct and rare conditions to arise. Atmospheric particles must be spherical, uniform, and form stable clouds that last for a long period of time. WASP-76 b's star needs to shine directly at this patch of atmosphere, and for us to see it, our instruments would also need to be looking in just the right place, at just the right time. ☺

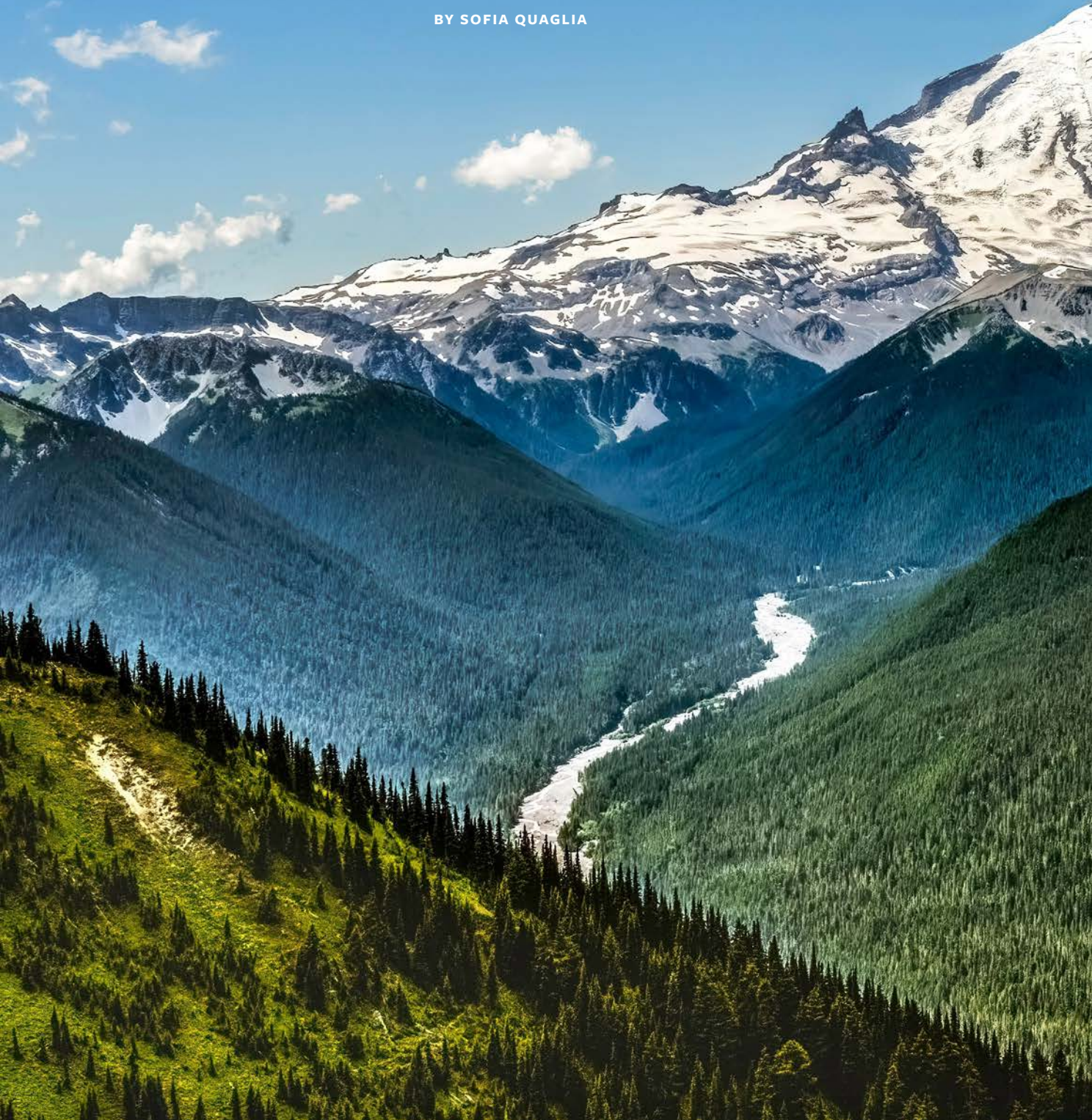


CLAIRE CAMERON is a science and technology journalist based in New York. Originally from Scotland, her work has appeared in various award-winning publications and international news outlets, including *Nautilus*, *Inverse*, *Semafor*, *Spectrum*, *Discover*, and the *Daily Beast*.

Paradise Lost

A dying glacier harbors mysterious species and ecosystems yet to be understood

BY SOFIA QUAGLIA







ASHINGTON STATE'S MOUNT RAINIER is one of the snowiest mountains in the world. Over the years, all of that snow has birthed dozens of living glaciers, which flow across the landscape. One such resident, the Paradise Glacier, drapes onto one side of the mountain at more than 8,400 feet above sea level. It cascades over the peak with a thick icy sheen. Here, the air is crisp and quiet.

Paradise Glacier is smaller than many of its majestic, icy neighbors—it is meek, now covering less than a quarter of a square mile. But, says Scott Hotaling, a professor of watershed sciences at Utah State University who has spent more than 500 hours roaming the glacier, even small mountain glaciers don't feel so small when you're on them.

"You can stand on one side of it and you can't see where it ends on the other side," he says of Paradise. While on the glacier, in what might seem to many people a barren environment of rock, snow, and ice, Hotaling says he can feel the abundance of life pulsing below him. He can feel its precise layers and intertwined stories.

"These glaciers are actually way more diverse than anyone realizes," he adds. Microbes adapted to life at the extreme, hardy tardigrades, and mysterious ice worms that crawl to the surface only under the cover of night, blooms of algae as bright red as blood, and even roving wolverines, all depend on this glacier. And as Hotaling and other glacial ecologists are finding, science is just scratching the surface of life in this one well studied glacier: Melting down a small bit of glacial ice here can reveal genetic traces from every domain of life. To say nothing of the many lesser-studied glaciers around the globe.

"It's a wild place," says Hotaling, who has spent years studying Paradise's hidden ecosystems. But as the glacier—and so many others—are at risk of imminent death by global warming, he and his colleagues worry we're losing more life than we can fathom.

THE STORY OF LIFE in a glacier can be told from the bottom up.

Where the glacier meets the bedrock, the subglacial zone, is among the most exotic. Because this part

of the glacier has very little oxygen and—being up to 100 feet under ice—receives very little light, it is rife with microbes that have adapted to extreme conditions on Earth.¹ Here, chemolithoautotrophic bacteria harvest their energy from breaking down iron and sulfur in the weathering bedrock below. Methanogens and methanotrophs feed off methane when there is no oxygen around them. Other microbes decompose ancient organic carbon found in the rock. Nutrients and flecks of carbon make their way to the bottom through slivers of meltwater seeping through fissures in the ice; sometimes they puddle in small lakes of freshwater, locked inside the glacier. And Hotaling notes they are only just starting to learn about the many wild lifeforms eking out an existence in this obscured niche—with more new interactions being discovered every time scientists are able to look. "There's just a lot of really kind of crazy stuff that happens down there," he says.

Above this zone sits a thick layer of ice, from 30 to nearly 100 feet, known as the glacial zone. Pockets of life may accumulate in splinters and cracks in the ice. Surviving here, inside the pressurized freeze, is challenging. "This area is dark. It has very few nutrients. It's very cold," says Hotaling.

But, ascending through the ice, the hot spot of activity on a glacier is a lot like where life is most abundant in the ocean: The top 2 inches of the glacier appears to be where the majority of its biological activity occurs. This area is covered in snow for part of the year, during the winter. And in warmer seasons, it is an area where the glacier's ice is exposed. Hotaling and colleagues sampled clumps of snow from the top of Paradise Glacier in 21 different spots over 5 months and found more than 4,700 types of bacteria and more than 3,000 types of fungi.²

“The different domains of life are all represented,” says Daniel Shain, a zoologist from Rutgers University who has studied microbes in Paradise Glacier with Hoteling for several years. Shain does something called a metagenome analysis of glaciers: He takes samples of glacial ice, melts them, extracts their environmental DNA, sequences it to figure out what’s there, and uses that data to model how glacier-bound organisms thrive in such a harsh environment. While he has yet to do a metagenomic analysis of Paradise, he has dived into that of similar glaciers in Alaska. What the findings suggest is that organisms that live in and on the top layers of ice and snow seem to have figured out a way to make more energy with fewer resources, compared to typical, terrestrial soil organisms.³

The top inches of the glacier are also home to reddish and blood orange colored, cold-loving snow algae, *Sanguina* algae, which create what hikers often call “watermelon snow.” During the winter months, when snow is thick and light is sparse, these algae species lie dormant inside the snow-pack as cysts buried up to some 10 inches deep. But during spring and early summer, the cysts germinate, and the algae migrate to the surface of the soft snow, where they bask in the sun, accumulating red carotenoids like we accumulate melanin in our skin, to protect their cells from UV and heat. Given their deep color, the algae also darken the surface and increase the rate at which ice on the glacier melts by as much as 20 percent. This produces little dips in the glacier—like little dimples in its face—where

*They emerge
by the billions.
Protruding out
of the snow like
hair growing out
of a scalp.*



LIFE ON ICE Notoriously hardy tardigrades—who can survive conditions even in outer space—make a living in the glacial ice on Paradise, feeding on algae and other scarce victuals scavenged in the harsh realm.



VANISHED CAVES

Paradise Glacier once held enormous ice caves—which were popular attractions for hikers and tourists, such as this person photographed in one of the glacier's caves in 1923. In the past few decades, the last of the caves have melted away.

bacteria and other microorganisms can make a better living, in turn, helping to keep the water from freezing again with the energy they produce through their metabolism.

Like grass in a pastureland, the algae feed miniscule grazing animals on top of the glacier, whether it is ice or snow, including rotifers, arthropods called springtails, and tardigrades—the chubby, gummy-bear looking animals known for their astounding ability to thrive in extreme conditions (including outer space). These and other hardy microinvertebrates, no larger than

about 0.02 inches long, contribute to much of the nutrient cycling and decomposition that occurs on the snowfield overlaying glaciers. (Even if it is orders of magnitude lower than the nutrient cycling that happens among grassland, for instance.)

But in Paradise Glacier, these critters are less abundant—and much more difficult to find, says Shain—than in many other glaciers around the world. That's because they face competition from one of the most bizarre of the glacier's residents: ice worms.

LAWRENCE DENNY LINDSLEY / WIKIMEDIA COMMONS

After living in the deep darkness of the ice through much of the year, as spring rolls around, every afternoon, as soon as the sun starts to set, half-inch-long ice worms make their way out of the ice and through the snow. The threadlike worms wriggle upward and migrate to the surface: They emerge by the billions. Protruding out of the snow like hair growing out of a scalp. Not much is known about them—what they do during the winter, how they survive in the ice despite not being able to withstand temperatures below freezing, or why they come out just at night. But Shain's work has found that, like glacial microbes, ice worms are also exceptional at creating energy inside their cells.

"That helps to explain why ice worms are the only macroscopic organism that lives on ice," says Shain. "Everything else is really, really small. Ice worms are a big outlier." (Another strange ice worm fact is that they have also evolved to be "one of the most UV-resistant organisms that we know of," says Shain, perhaps to make do as light-absorbingly dark creatures living so close to the sun; though their nocturnal habits raise still more questions about this adaptation.)

On the surface of the glacier, together with ice worms, insects called ice crawlers roam over from their terrestrial hiding places at the edges of the glacier. Known to science as grylloblattids, the inch-long insects with cockroach faces and no wings scavenge on the glacier's surface, picking up any nutrient-rich debris that's been blown there by the wind: dust, pollen, ash from wildfires, smaller organisms, and other insects blown in by too strong a gust and marooned on ice.

THE LAST OF PARADISE

Paradise Glacier is about 12 percent of the size it was when it was mapped in 1913. One expert expects the last bits of this glacier will vanish by 2040.



“When you have a big ice cave, you’re in the heart of the glacier, and it means the heart is no longer beating.”

Birds from above, in turn, fly onto the ice, plucking ice crawlers and ice worms out of the snow and into their hungry bills.⁴ Songbirds, including the great crowned rosy finch, perch on the soft snow, together with mountain bluebirds, ravens, white tailed ptarmigans, American kestrels, horned larks, and American pipits.

But, as a small bird, a glacier is a dangerous place to forage, says Hotaling. A dark-backed bird loitering on a widespread white surface is an easy target for a bird of prey, and raptors and hawks are known to patrol glaciers, swooping down and snatching songbirds off the peaceful snow. In fact, Hotaling has noticed that, when foraging, songbirds like the rosy finches tend to stay near the margins of the ice, likely so they can easily get onto the rocks where there are places to hide if a hunting raptor dives.

Bigger animals, including mountain goats, hoary marmots, Cascade red foxes, or even wolverines, lie down to rest on the glacier’s ice to cool down from the beating summer sun, and use the snowpack to travel from one side of the mountain to another. In summer 2021, Hotaling put camera traps all over the glacier and captured photographs of the first family of wolverines on the glacier in that area in more than 100 years.⁵

The glacier supports life downstream, too. As the snow and ice thaw, meltwater from Paradise Glacier births the eponymous Paradise River. Here, where the ice becomes water just above 39 degrees Fahrenheit, life changes radically.

In the coldest first reaches of the seasonal melt, the melting ice brings dissolved organic carbon, which,

activated by sunlight, clings in a nutritious biofilm on top of the bedrock: It feeds the largest animals found here, such as aquatic insects, black fly larvae, and stone flies, including a rare species known as the northern forestfly. Slightly farther downstream, life gets bigger, large fish appear, including various salmon species, the endangered bull trout and cutthroat trout, sculpins, and whitefish.

Humans, too, rely on Paradise Glacier. The glacier’s meltwater provides irrigation for agriculture downstream, drinking water to nearby communities, and it eventually feeds into hydropower plants such as the Alder Dam farther down on the Nisqually River. And hikers and mountaineers make their way up the river and onto the snow for scientific research, for recreation and sport, or for artistic inspiration.

THE MOUNT RAINIER LANDSCAPE has hosted the Cowlitz, Muckleshoot, Nisqually, Puyallup, Squaxin Island, Yakama, and Coast Salish people for millennia. Archeological artifacts suggest that—while the mountain was fully covered in ice and snow up until about 9,000 years ago—ancestors of these tribes were foraging, hunting, and gathering on the slopes as soon as the first plants and trees sprang up. Records suggest they’d collect huckleberries or hunt mountain goats and gather cedar bark to make baskets and hats.

By the late 1700s, European and American visitors became captivated by the landscape of the mountain and its glaciers, too.

“Of all the fire mountains which like beacons; once blazed along the Pacific Coast, Mount. Rainier is the noblest,” wrote the Scottish-American writer and conservationist John Muir, who climbed the mountain in 1888.

Yet, the noble mountain is losing its blaze.

Paradise Glacier, for one, is dying.

“Right now, it’s about 12 percent of the size that it was in 1913 when it was mapped,” says Mauri Peltó, director of the North Cascades Glacier Climate Project at Nichols College, of the glacier.

The first time he visited Paradise, in 1985, Peltó stepped inside its large, long-famous ice caves, which had been a draw for tourists since at least the early 1920s, when people could access part of the then-massive glacier more easily from roads. While mesmerizing, the ice caves were already a sign of the glacier’s decay. “When you have a big ice cave, you’re in the heart of the glacier, and it means the heart is no longer beating,” says Peltó, quoting his daughter, with whom he’s hiked up to the glacier several times. “Because if a glacier is moving and alive, it won’t allow a big cavity like that to form.” Shortly after Peltó’s first visits, in the late ’80s, that lower part of Paradise Glacier melted away and was proclaimed dead—the upper part of Paradise Glacier is all that’s left now.

“Paradise is just following the path of the Stevens Glacier, the Van Trump Glacier, and the Pyramid Glacier; they are all gone now,” says Peltó of the other glaciers that once adorned Mount Rainier. At the rate it is melting, Peltó speculates, we’ll bid goodbye to the Paradise Glacier—and all of the life inside and on it, discovered and not—within 15 years.

As the glacier rapidly dies, late in the summer, when the climate is dry and warm, it is also already producing 80 percent less runoff than it used to, says Peltó. This means the streams it feeds may become depleted and see their temperature increase rapidly, affecting the life of all of the aquatic invertebrates that have adapted over millennia to the frigid waters, and all of the fish swimming, feeding, and reproducing in the rivers below.

There may be some unlikely survivors, though. Shain, for instance, has a hunch that, despite their name, the ice worms may be best poised to weather the heat.

Geological data suggest that the Pacific Northwest has experienced multiple warm periods over the past

several million years, with temperatures getting even a few degrees warmer than the area is experiencing now, and the glaciers fully melting. Yet genetic data Shain’s collected suggests ice worms may have been around in that part of North America for millions of years, meaning that they somehow survived those warmer eras.⁶ The worms cannot migrate long distances, so they cannot have come from very far.

Maybe even in the direst of warming scenarios, there will be pockets of ice that persist, where the creatures of the glacier can find refuge throughout the decades, says Shain. Given how little we know about ice worms—and how little we know, to be honest, about so much of life in glaciers—maybe there is also a silver lining in our ignorance: potential to be surprised. 🌀

SOFIA QUAGLIA is a freelance journalist writing about all things science and nature and how we talk about them. Her work has appeared in *The New York Times*, the BBC, *National Geographic*, *The Guardian*, *New Scientist*, and more. She’s on a mission to visit the entire planet by spending each month in a different country, so she’s been living on the road since 2021.

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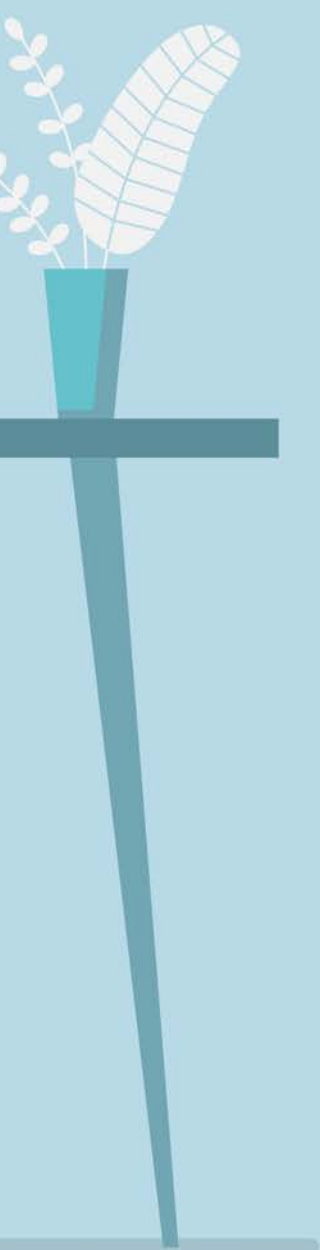
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Is the State of the World Causing You Pain?

There's a German word for that feeling

BY TIM BRINKHOF



THESE DAYS, MANY PEOPLE STRUGGLE to keep up with the state of the world without being overcome by a sense of despair that's as profound as it is difficult to describe. Unless you happen to speak German.

The German language, a popular saying goes, has a word for everything. There's *Schadenfreude* and *Zeitgeist*, of course. But it's perhaps time we get more acquainted with *Weltschmerz*, a word which literally translates to "world pain."

Coined by the German writer Johann Paul Richter in his 1823 novel *Selina*, *Weltschmerz* has been used by scholars to signify a unique type of sorrow that is linked not to personal hardship but the hardship of others; not to one's own misfortune, but the misfortune of the world at large. It pervades certain works of literature and philosophy, from Wolfgang von Goethe's *The Sorrows of Young Werther* to Arthur Schopenhauer's *World as Will and Representation* and was characterized by one critic as "abnormal sensitiveness ... to the moral and physical evils and misery of existence."

It may have been birthed more than two centuries ago, but *Weltschmerz* seems to be increasingly rearing its head in blog posts, YouTube videos, and self-help books that discuss how social media, global warming, political unrest, and other fixtures of 21st-century life are eating away at our collective mental health. This imposing word neatly encapsulates the mix of sadness, hopelessness, fear, distrust, and rage that many of us feel while doomscrolling our way through seemingly endless supplies of disturbing and disheartening headlines.

Weltschmerz literally translates to “world pain.”

Whether *Weltschmerz* is indeed a particularly strong element of our current *Zeitgeist* or a feature of the individual human condition is difficult to say, largely because research on the specific psychological phenomenon remains all but unexplored by science.

To study *Weltschmerz*, of course, you first have to properly define it. This is easier said than done. The German poet Heinrich Heine, who died in 1856, described it as rumination on the “transience of life on Earth,” framing it as an existential issue. Ralph Ellison, who referenced *Weltschmerz* in his 1952 novel *The Invisible Man*, appears to have connected it to generational trauma, in this case as a Black person in America. The Cambridge Dictionary defines *Weltschmerz* as a “feeling of sadness and lack of hope about the state of the world.” Merriam-Webster, as “depression or apathy caused by comparison of the actual state of the world with an ideal state.”

These diverging, at times contradictory interpretations call the precise nature of *Weltschmerz* into question. Does it stem from—and take the shape of—pessimism or optimism? Nihilism or idealism? Apathy or care?

THE MOST OBVIOUS RISK FACTOR for flare-ups of *Weltschmerz* is exposure to the suffering of others. Research has long shown that people who interact with traumatized individuals—including emergency medical services personnel and family members of the terminally ill—are at risk of experiencing psychological distress themselves. More recent studies indicate that this distress, sometimes referred to as vicarious or secondary trauma, can develop even without direct contact, including through social media imbibing and

news consumption. This suggests *Weltschmerz* is more common today than it was in the past, when dispiriting news of world events were not delivered directly to our pockets 24/7.

Another possible risk factor is the way people construct their sense of self. According to Marc Williams, a clinical psychologist and an honorary senior lecturer at Cardiff University in Wales, the emotional impact of events we experience has less to do with the event itself than the meaning and weight we attribute to it. “What feels impersonal to one person may feel deeply personal to another,” he says. In previous centuries, people’s inner circles were limited to their families and towns. Today, thanks to factors like mass migration and technology, our in-groups—and, by extension, sense of self—readily transcend borders, languages, and cultures. And as our identities expand, so does our concern for those with whom we identify. And it can even extend beyond the human, Williams says. “For climate anxiety, for example, research has found associations with higher levels of nature connectedness, or identification with the natural world.”

Identity, then, opens the door to another potential risk factor: affective empathy. Whereas cognitive empathy refers to the ability to understand someone else’s thought processes, affective empathy is the capacity to feel another’s emotions. Affective empathy helps us form and maintain relationships, but excessive or unregulated empathy can lead to what Williams describes as “emotional overload, the psychological burden of continually feeling others’ pain”—a burden which increases susceptibility to psychological distress, psychiatric disorders, and perhaps *Weltschmerz*.



I'D WERTHER NOT

Weltschmerz has run as a trope through literature and philosophy for more than two centuries. This state of being has tormented protagonists from the unnamed hero of Ralph Ellison's *The Invisible Man* to Wolfgang von Goethe's poor Werther, pictured here.

The mental discomfort produced by *Weltschmerz* needn't be paralyzing.

One final factor is cognitive dissonance, defined in one literature review as frustration that arises when “people are confronted with facts that contradict their beliefs, values, and ideas.” Though not always emphasized in equal measure, disjunction between personal expectations and perceived reality is a recurring theme in literary and philosophical *Weltschmerz* discourse. Miles Groth, an existential therapist, expert on continental European philosophy, and professor emeritus in psychology at Wagner College in New York City, suggests that the idea of *Weltschmerz* arose at a very specific time: when “religious feelings that suffering is inevitable disappeared from the West.”

Indeed, whereas people from the devoutly Christian Europe of the Middle Ages are thought to have accepted and found comfort in the fact that everything—including evil—was part of God’s divine plan, those born in later centuries tended to operate according to a different set of expectations. Where faith gave way to science, the evils of pain, suffering, and injustice came to be regarded as avoidable, unnecessary, and by extension intolerable.

In this sense, *Weltschmerz* could be framed as an expression of the shattered assumptions theory. Formulated by social psychologist Ronnie Janoff-Bulman in her 1992 book *Shattered Assumptions: Towards a New Psychology of Trauma*, this theory proposes that certain experiences are traumatizing in large part because they dismantle our most basic assumptions about existence.

Even getting this information third-hand, for example by doomscrolling, might spark a similar reaction. A 2024 study in Iran and the United States found that social media exposure to “meaning-threatening” stimuli, such as famines and genocides, can cause existential anxiety as well as misanthropy: mistrust and hatred of humanity and even oneself. While existential anxiety matches Heine’s definition of *Weltschmerz* (preoccupation with the ostensible shortcomings of existence), misanthropy evokes *Weltschmerz* as expressed in the work of Schopenhauer, whose pessimistic attitude toward human civilization led him to prefer a life of asceticism and solitude.

AS FOR WELTSCHMERZ’S CLINICAL applications, it’s possible that the condition is merely a symptom of other, better defined and more extensively researched psychiatric conditions. After all, Heinrich Heine, Friedrich Hölderlin, and Nikolaus Lenau—German poets whose unwaveringly melancholic oeuvres form the bedrock for both literary and philosophical inquiries into *Weltschmerz*—all had complicated medical histories, having retrospectively received diagnoses for either severe depression or schizophrenia.

Thomas Pyszczynski, a professor emeritus of psychology at the University of Colorado, Colorado Springs and one of the founding fathers of terror management theory (which posits fear of death as a key motivator of behavior and mental well-being), is

collecting data on people experiencing “psychological distress” in response to Donald Trump’s political career. He suggests that his study subjects may not be feeling what constitutes *Weltschmerz* but rather a “subclinical form of PTSD” that “could reach clinical significance in some people.”

Aaron Fisher, an associate professor of psychology at the University of California, Berkeley, cautions against classifying *Weltschmerz* as a distinct psychological phenomenon, arguing that, in both clinical and research settings, the focus should be on the way we respond to stimuli, not the stimuli themselves; on the output, not the input. So, he said, stressors “need not be classified as ‘world’ vs. ‘community’ vs. ‘self,’” and making too big of an effort to do so yields “diminishing returns.”

Williams, by contrast, *does* propose that *Weltschmerz* can be distinguished from other psychiatric conditions. While clinical levels of depression and anxiety can be debilitating, *Weltschmerz* need not result in functional impairment. “It can be a deeply felt experience without meeting the criteria for a mental health problem,” he says. Something like climate anxiety encompasses a broad range of emotions and relates not only to “inner suffering but also moral distress,” making it difficult to categorize as a psychological condition.

The mental discomfort produced by *Weltschmerz* needn’t be paralyzing—and actually might in many cases serve as a source of motivation. Williams notes that a recent study he was involved in found that climate anxiety was associated with high levels of “intention to engage in pro-environmental behaviors.” The same can be said about anxiety regarding political events, with one 2023 study finding that people who reported “more politics-related negative emotions” also “reported greater motivation to act on political causes by doing things such as volunteering or donating money to political campaigns.”

Whether activism can be used to treat *Weltschmerz* depends on the situation. In some cases, joining other people in working toward achieving a common goal can indeed provide a welcome feeling of purpose and community, improving our mental health. In others, lack of progress toward achieving such goals—especially lofty ones like ending global poverty or convincing governments and corporations to work together to mitigate global warming—can actually have the opposite

effect: reducing our sense of agency and fueling the very despair we wish to keep at bay.

On the flipside, *Weltschmerz* can also be treated by retreating from the outside world. This remedy was one used by Schopenhauer, who, convinced that the problems plaguing the world were both endemic and unsolvable, spent much of his adult life in self-imposed isolation from society. Today, Schopenhauer’s preferred treatment plan survives in the form of both physical and especially digital detoxes. But while research shows that taking a break from the doomscroll-inducing algorithms of social media platforms has noticeable psychological benefits, the strategy is ethically thorny. By deleting TikTok and turning off the evening news, we’re turning a blind eye to suffering in ways that those less fortunate than us cannot.

In clinical practice, the most effective treatments for *Weltschmerz* balance engagement with disengagement, a middle ground between taking action where possible and recognizing what is and isn’t beyond our individual control. As Cynthia Shaw, a clinical therapist specializing in existential anxiety and founder of Authentically Living Psychological Services in New York City, explains:

“One of the hardest parts is walking the line between validation and paralysis. You can’t reassure someone that everything will be fine, because they’re right, some things aren’t OK,” she says when I asked her about how people can best manage *Weltschmerz*-related distress without compromising their moral values. “And yet, staying in a perpetual state of despair isn’t sustainable either. So, the goal in therapy isn’t to ‘fix’ the world, nor the person. It’s not about not caring. It’s about figuring out how to care differently.” ☺

TIM BRINKHOF is a Dutch-born, Atlanta-based journalist who reports on culture, history, and science. He studied at New York University and has written for *Vox*, *Slate*, *Esquire*, *The Village Voice*, and more.



The Surprising Benefits of Wild Orbits

*Irregularities in a planet's swings might make a more
biology-friendly climate*

BY SEAN RAYMOND



EARTH'S HISTORY HAS BEEN PUNCTUATED by at least five major ice ages. Some of these frigid periods of prolonged global cooling saw much of our planet locked in ice and snow for 100 million years. It may seem counterintuitive, with the current anthropogenic warming that Earth is experiencing, but we're actually in the midst of one—the Quaternary Ice Age—that started about 2.6 million years ago. (Thankfully, within the broader context of our current ice age, we've been experiencing an interglacial period, when ice sheets and glaciers are melting and contracting, for the past 11,000 years or so.)

The term "Ice Age" conjures images of woolly mammoths roaming snow-encrusted plains and human ancestors grunting across the frozen landscape, hunting them, barely scraping by in a harsh environment. But we might, in fact, owe a great debt to Earth's grand and dramatic shifts. In fact, scientists are coming around to the idea that wide vacillations in a planet's climes might actually be a hallmark of habitability. And the drivers are of a cosmic scale.

Earth has progressed through long periods of colder and warmer climatic conditions in large part because the planet, on its elliptical orbit around our nearest star, shifts slightly both in terms of its orbital path and in the degree to which it is tilted toward or away from the sun.

This insight, as established as it is today, took decades to solidify and support with astronomical evidence. Western astronomers have known that the Earth's orbit is not perfectly round since Johannes Kepler reported back in the early 17th century that the planets' trajectories around the sun are actually ellipses.

We might owe a great debt to Earth's grand and dynamic shifts.

Yet the exact shape of Earth's orbit—its eccentricity, a measure of an orbit's non-circularity—is constantly changing. Earth oscillates between being a near-perfect circle (with an eccentricity of less than 1 percent) up to a maximum eccentricity of about 6 percent about every 100,000 years.

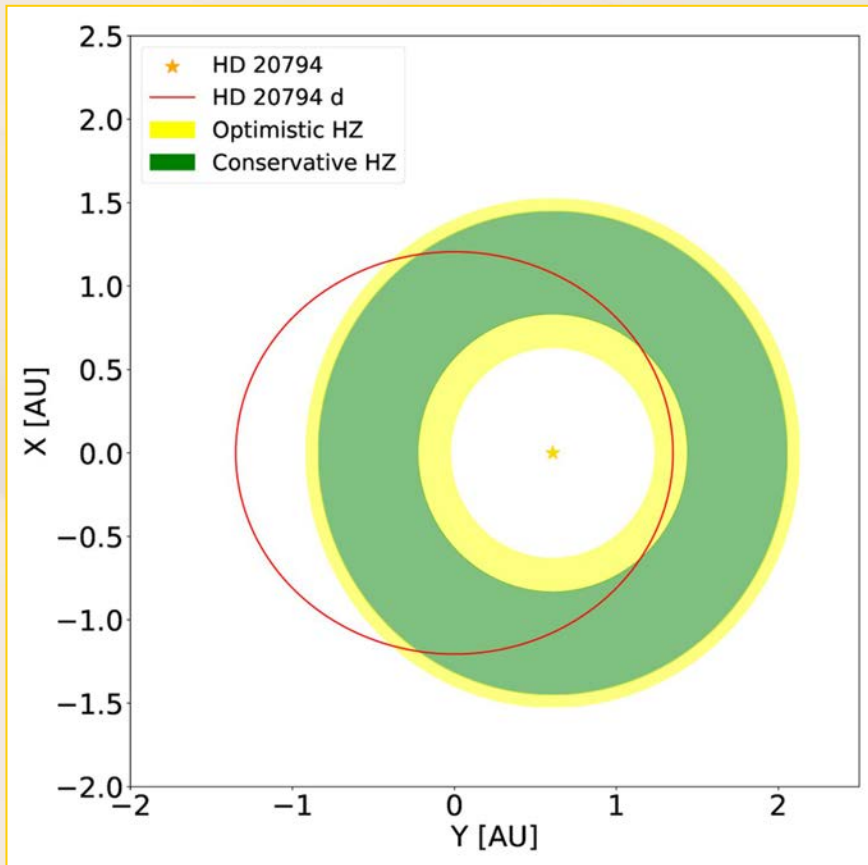
Meanwhile, Earth's tilt on its axis, or obliquity, oscillates between about 22 and 24 1/2 degrees roughly every 41,000 years. The obliquity (which is currently 23 1/2 degrees) is what determines the strength of the seasons, as well as the width of the tropics. The direction that Earth's spin axis is slowly shifting as well, oscillating on a timescale of some 26,000 years and causing a slow shift in the positions of the stars in the sky, is the planet's precession.

But it wasn't until the early 20th century that Serbian astronomer Milutin Milanković developed the theory that astronomical changes drive variations in our climate. He asserted that Earth's ice ages must correlate with Earth's orbital eccentricity, obliquity, and precession. Decades later, in 1976, a landmark study led by Earth scientist James D. Hays of Columbia University used ocean floor sediments to confirm the cyclical nature of ice ages, showing that there are indeed timescales imprinted on Earth's past climate that reflect the 26,000-, 41,000-, and 100,000-year timescales inherent in the oscillation of Earth's orbital

shape and spin. This was some of the first concrete evidence of the existence of what are now called Milankovitch cycles.

Now, many astronomers who are searching far and wide for planets that might be capable of supporting life are gathering evidence that the more extreme a planet's orbital and positional oscillations, the more hospitable it may be to life.

Traditionally, the thinking has been that a perfectly circular orbit gives a planet the best chance for developing and hosting life. Of course, there are plenty of other factors that are key ingredients in the recipe for life—at least, life as we know it. One of the main ones has been orbital distance from a star, which translates to the average planetary temperature and leads to the concept of the “habitable zone,” the Goldilocks-esque belt around a star in which a planet's climate could be just right—neither too cold, nor too hot—to harbor liquid water. A potentially habitable planet must also have an atmosphere that is not too thick or thin, to let in just the right amount of star-borne radiation for heat and energy. Plate tectonics may help as well, shifting slabs of a planet's outer layer bringing vital elements and heat up from its core. These constraints aside, it is only in recent years that a planet's orbital eccentricity and obliquity have come to be considered significant factors in habitability.



ALL IN THE WOBBLE

A recently discovered exoplanet, HD 20794 d, orbits its star in an elliptical orbit. This oblong path would put it in either an optimistic or conservative habitable zone for a large chunk of its year.

The picture emerging now is that planets that experience wild swings in their eccentricities, obliquities, *and* precessions may be “superhabitable.” This could mean that ice ages coming and going could signal a planet that is more likely to host biological organisms than one with a more steady climatic history, as first explored in a pioneering 2014 paper by René Heller, then at McMaster University, and John Armstrong from Weber State University.¹ And it could also greatly increase the number of likely suspects for life-bearing planets in our universe.

A SLEW OF RECENT STUDIES have used computer simulations to model the hypothetical conditions on rocky exoplanets with exotic orbits and spin states. What they show is that, contrary to the standard thinking, both land-dominated and ocean-dominated

planets appear to benefit from having extremely elliptical orbits or very tilted spin axes. Earth-like planets on non-Earth-like orbits might be just as likely as Earth to harbor life—maybe even more likely. Given the abundance of non-circular orbits among exoplanets—with half of all gas giants having eccentricities larger than 25 percent (that is, with orbits more than five times more stretched-out than Jupiter’s or Saturn’s)—this opens up a new landscape of planetary habitability.

A 2023 study, published in *The Astrophysical Journal*, modeled what might make such a “superhabitable” planet.² The study, by Jonathan Jernigan and colleagues at Purdue University, coupled a climate model to a 3-D biogeochemical model, which mathematically captures the main chemical reactions that nourish Earth-like marine life while also taking into account factors such

NARI, N., ET AL. ASTRONOMY & ASTROPHYSICS (2025).

as ocean circulation and heat and salinity transport. The researchers showed that the biological productivity of the oceans on these hypothetical planets increases with more eccentric orbits or higher obliquity because, with these sorts of variations, the increased surface temperature variations cause vertical mixing in the oceans to increase. Vertical mixing is sometimes called the “biological pump,” as it transfers organic material from the upper layers of the ocean where photosynthesis is active down to the depths, and brings nutrients from the depths back up. The study found that increasing the obliquity all the way up to 90 degrees or the eccentricity up to 40 percent can increase the total productivity of the oceans by up to a factor of 3 to 4. The productivity in a given area was strongly seasonal, but the net effect across the globe was a significant increase in productivity relative to a zero-obliquity planet on a circular orbit.

This result expands the habitats that are relevant in the search for life in the universe. Among the more than 5,000 exoplanets discovered to date, there are currently 29 rocky planets in the habitable zone. Most of these planets are found in systems with other similar-sized planets and occasionally ice giants or gas giants—and many other planets may be lurking below our current detection thresholds. Their fellow planets cause oscillations in the rocky planets’ orbital eccentricities and spins that could span a wide range in both amplitude and timescale. Such planets would traditionally have been discounted as being unlikely to be fertile, but this model suggests just the opposite.

But need the extremes be so extreme? In a study published earlier this year, a team led by Paul Lerner at Columbia University and Goddard Institute for Space Studies, performed a similar set of simulations but with a different code and technique.³ They found that biological productivity in the oceans increased modestly (by up to 15 percent) for obliquities as high as 45 degrees, but then decreased for higher obliquities.

Such swings also seem to be helpful in creating life-conducive conditions on land. A 2024 study led by Bingham Liu at the University of Leeds found that the surface habitability of planets like Earth increases for eccentric orbits.⁴ The team simulated the climate for a circular orbit and one with an eccentricity of 40 percent—in both cases with zero obliquity. The planet with the eccentric orbit, in their model, gained a good

chunk (more than 25 percent) of land that would have a temperature range ideally suited for life (between 32 and 122 degrees Fahrenheit) over the planet with a perfectly circular orbit. The simulated eccentric-orbit Earth was warmer overall (by a couple of degrees). This increase in warmer terrestrial space was due to the fact that the air circulation patterns on the eccentric Earth-like planet were more effective at lifting warm air from the equator and moving it to higher latitudes.

And a recent study published in *Science* has been able to tease apart the separate influences of variations in Earth’s eccentricity, obliquity, and precession. The team, led by Stephen Barker of Cardiff University in the United Kingdom, shows how the duration and severity of ice ages are connected with those three factors.⁵ In short, these dynamics determine the amount of solar energy received by the Earth. When its orbit is non-circular, Earth receives more energy from the sun at its closest approach to the sun. At the most extreme, this can result in a 25 percent increase in solar energy at its closest approach relative to its farthest approach. Where this energy lands on the planet depends on the obliquity and on the precession. The higher the obliquity, the more energy is received by northern latitudes. But this only happens if Earth’s spin axis is pointed toward the sun; if it is pointed away, then the Southern hemisphere is more strongly heated. The Northern hemisphere currently contains far more land coverage than the Southern hemisphere and is where the most massive ice sheets tended to be located during the most recent ice age.

This approach also provides a new roadmap to predict future ice ages using Earth’s eccentricity, obliquity, and precession angle. Those variables create a predictable pattern for the duration of ice ages and interglacial periods, such as the current one. If this astronomically driven pattern continues, Earth will plunge into its next ice age in about 11,000 years and remain highly glaciated for another 55,000 years. Of course, given the dramatic human-driven changes to Earth’s climate that have already taken place, it is quite possible that this pattern will be disrupted.

PREDICTING ICE AGES is not quite so simple as tracking one planet and its relation to its focal star. Milankovitch cycles are also heavily influenced by other planets.

If planets like our own are common out there then the chances for extant life in our own galaxy are looking good.

Earth's orbit and spin characteristics don't oscillate on their own. If the moon and the other planets in the solar system magically disappeared, Earth would continue to orbit the sun, but our planet's orbit and spin would look much different than it does now. Gravitational perturbations from the moon and other planets caused the oscillations that gave rise to the ice ages. Each planet exerts a gravitational force on the others, causing small deviations to their orbital shapes and spins. Given its titanic mass (more than 300 times Earth's), Jupiter has the strongest influence on the evolution of Earth's eccentricity. Earth's spin is likewise affected by the other planets, but even more strongly by the moon, which controls Earth's precession rate and strongly restricts the amplitude of obliquity oscillations. In a famous paper from 1993, Jacques Laskar and colleagues from the Observatoire de Paris showed that, without our unusually large moon, Earth's obliquity would evolve chaotically and could potentially reach values as high as 85 degrees, which would have our planet lying nearly on its side in relation to the sun.⁶

Many Earth-like exoplanets probably have Milankovitch cycles that are even more pronounced than ours. The orbits of the solar system's planets are surprisingly close to circular when compared with the known exoplanets. The orbits of known gas giant (Jupiter-like) exoplanets are particularly stretched-out, with typical eccentricities of 20 to 40 percent and some planets having

eccentricities above 80 to 90 percent. Which has implications for rocky, potentially habitable planets.

If Jupiter's eccentricity were increased from its current value of 4.4 percent to 40 percent, Earth's eccentricity would oscillate between zero and 25 percent (instead of our current maximum of 6 percent) every 135,000 years. If Jupiter's eccentricity were set to 20 percent but it was placed at Mercury's orbital distance from us, Earth's eccentricity would oscillate from zero to 10 percent every 3,000 years.

In simulations of the growth of rocky planets under the influence of gas giants, I have created systems in which a rocky planet in the habitable zone undergoes oscillations in eccentricity and in obliquity up to 10 times larger than those felt by the Earth. A decade ago, I would have written off such planets as unlikely to be habitable, but the tide has turned, and now I would consider them excellent candidates in the search for extraterrestrial life.

One recently-discovered planet just some 20 light-years away from Earth, HD 20794 d, has an eccentric orbit that passes through its star's habitable zone but spends a big chunk of time farther away, past the outer edge of that Goldilocks region. The planet receives about seven times more solar energy at closest approach compared with farthest approach to its star—that's 28 times more than the maximum variations felt by the Earth. With such giant swings, could this planet possibly be habitable?

The short answer is, yes. Planets are remarkably resilient to variations in energy, as long as the total energy received over an orbit is not changed (and they have a suitable mass and atmosphere). For more than two decades, scientists have used climate models initially developed to study Earth to also study the climates on Earth-like exoplanets. These models take into account the strong pulse in heat felt as a planet on an eccentric orbit passes close to its star, and the cold period when the planet is moving farther away from the star. A 2014 study led by John Armstrong at Weber State University, for example, showed that the habitable zone itself expands for planets undergoing large oscillations in eccentricity or obliquity.⁷ The outer edge of the habitable zone, beyond which planets freeze over and enter an irreversible snowball state, is effectively shifted outward, expanding the real estate of planetary habitability.

Some fascinating oscillating climates may exist. In a 2010 study, David Spiegel of Princeton University and his colleagues modeled the climate of a hypothetical planet with an oscillating eccentricity.⁸ In some cases, at low eccentricity, the planet froze over and became trapped in a “snowball Earth” state, whereby its reflectance became so high that it could barely absorb any incoming solar energy. Earth may itself have been trapped in a temporary snowball state multiple times during its history, only emerging after a million years or so, when greenhouse gases became highly concentrated in the atmosphere because the ice cover shut down rain-driven, water-rock erosive processes that normally lead to their removal. In this study, the planet emerged from the snowball state only when its orbit became eccentric enough that it received more solar energy and could thaw at the equator.

All signs point to rocky planets with large eccentricity or obliquity oscillations being as habitable as Earth, if not superhabitable. If planets like our own are common out there—and that’s a big if, because it’s awfully hard to define “like our own”—then the chances for extant life even in our own galaxy, with its 100 billion or so stars thought to have planets orbiting them, are looking good. Our vision of the dynamics of Earth-sized worlds will take a big step forward when the European Space Agency’s Gaia telescope

releases its catalog of thousands of giant exoplanets in the orbital range between roughly Jupiter to Saturn (expected in late 2026). Since these giant planets have such a strong influence on the orbital evolution of rocky worlds, those new data—in conjunction with modeling research—will help us identify bodies capable of supporting life farther afield than ever before.

I won’t be surprised if some of the best candidate planets for life are found in extreme systems, characterized by wild orbits. ☺

SEAN RAYMOND is an American astrophysicist working at the Bordeaux Astrophysical Laboratory in France. He also writes a blog at the interface of science and fiction (planetplanet.net) and published a book of astronomy poems.

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They Came for Climate Science. Then the Storms Came

*The administration's cuts to climate research are destroying
decades of science—and life-saving forecasts*

BY LOIS PARSHLEY



LONG BEFORE RICK THOMAN became a climate scientist—before the late-night calls with National Oceanic and Atmospheric Administration offices around Alaska and the long discussions with local tribal councils—he was just a boy in Pennsylvania who loved when it snowed.

Every morning in grade school, Thoman would carefully log temperatures from the thermometer outside his window, plotting it on graph paper and meticulously taping the sheets to his wall. Eventually, the chain snaked around the room, tracing his growing obsession with tracking the natural world.

That early habit became the foundation for a lifelong pursuit: Thoman has spent the past three decades translating complicated climate science for communities facing an increasingly unpredictable world.



At his office at NOAA's Alaska Center for Climate Assessment and Policy, where he is a climate specialist, Thoman's regularly peppered with questions from rural hunters asking about thin sea ice and pilots trying to plan fuel deliveries around erratic freeze-ups. In a state where climate change already disrupts daily life, he's been a link between science and the people it affects. Now, Trump administration cuts are threatening not just his job, but the essential tools that help him provide globally important data.

Since taking office in 2025, president Trump has rapidly dismantled climate science, undermining domestic research and international collaborations. In the process, services as basic as weather and storm forecasting are suffering. Scientists warn that the administration's series of drastic cuts and political manipulation of federal funding and data will stall critical research, hinder disaster preparation and response, and damage the United States' global standing—spilling beyond science.

In accordance with Project 2025 recommendations, this spring the president's budget proposed reducing NOAA's funding by \$1.7 billion, calling for steep cuts to its operations, research, and staff. That cut, much of which is still on the table, could eliminate whole programs that conduct vital weather, ocean, coastal, and climate research, weakening forecasts and making it harder to prepare for disasters. The administration has also called for ending numerous satellite, ocean, and coastal monitoring initiatives, and taking down other key weather and climate infrastructure, including models that help forecast hurricanes or track ocean acidification.

For Thoman, a grim uncertainty has hung over each morning as he braced for word that NOAA funding for the Alaska Center for Climate Assessment and Policy was cut. Any time his phone buzzed, it could spell the end of his being able to provide crucial, daily-life information from datasets that have taken decades to build. "Every day you open your email like, *Is today the day?*" he says.

THE LIST OF CLIMATE and science programs that have been cut or are on the chopping block continues

"We could wake up the next day, the hurricane could be right next to the coast."

to grow, a grim roll call the Union of Concerned Scientists calls "a wholesale attack on the democratic systems upon which this nation was built." Since Trump's inauguration this year, the group has documented 402 cases in which government officials have censored, distorted, or eliminated federally-funded scientific work. This includes critical Environmental Protection Agency climate and

energy research, Department of Interior funding for energy and development programs and wildfire suppression, Department of State's climate investment programs, key NASA satellites used for climate modeling, and a U.S. Geological Survey program that studies how key ecosystems are changing.

"We are driving a dagger straight into the heart of the climate change religion," EPA administrator Lee Zeldin said in an official statement describing the agency's rollbacks. After a recent climate report bent the science so clumsily that its own sources spoke out, federal agencies are losing credibility. Staff at the NSF, NASA, and the EPA have all now signed public statements protesting the administration's changes. Many of them have since been placed on leave.

The implications tumble far beyond the U.S.'s borders. Thoman explains that in May, the Trump administration announced it would end NOAA services that monitor Arctic sea ice and snow cover. While other nations also collect ice data, it's far less specific than NOAA's for many areas, including Alaskan waters. Any ships navigating the Northwest Passage, for example, which is increasingly eyed for faster shipping routes for all kinds of goods, count on ice information from this program. Over the next two months, NOAA and the Department of Defense went on to announce three different dates for when the sea ice program would be terminated. (It was only rescued when the National Snow and Ice Data Center—run out of the University of Colorado, Boulder—was able to pivot to using data from a Japanese satellite.) The back-and-forth changes, Thoman says, were a "fiasco" that left the climate community worried about major gaps that might undercut climate models' accuracy.



FEWER EYES IN THE SKIES Proposed cuts from the administration would eliminate numerous satellite missions, including Department of Defense data to help better understand hurricane dynamics and NASA data for climate modeling. These cuts would undermine forecasting local disasters as well as the global climate disaster.

Thousands of miles away, James Potemra, an oceanographer at the University of Hawaii, sees how the U.S. stepping back from data collection will put people in that region—and around the world—at risk.

The biggest climate concerns for many Pacific islands are extreme weather, especially storm surge affecting low-lying coastlines, and threats to coral reefs from ocean warming that endanger tourism. Because freshwater can be scarce, communities also rely on seasonal forecasts to prepare for dry periods and manage limited water resources. Much of this information previously came from U.S. National Weather Service offices in Honolulu and Guam, which, as in many places, have been downsized this year.

Other satellite data crucial for understanding the internal structures of hurricanes, previously provided by the Department of Defense, are also at risk of vanishing. Marc Alessi, a fellow at the Union of Concerned Scientists, says this data is very important for identifying when a hurricane might undergo rapid intensification.

Without it, he says, “we could wake up the next day, the hurricane could be right next to the coast, and no one would have known how strong it became overnight.”

MOST AMERICANS CHECK THE WEATHER without knowing that nearly every forecast they see—whether on their phone or on TV—comes from publicly funded NOAA data. Behind those daily predictions are government scientists, experts who’ve devoted their careers to translating the atmosphere’s chaos into something we can plan around. Since January 2025, approximately 2,200 of them have lost their jobs, and many more have taken early retirement offers. Altogether, NOAA has lost about 10 percent of the agency’s workforce. “One of the big, big impacts,” Thoman says, “is something that’s still intangible: The loss of many people with long experience.”

The effects are already rippling across Alaska. Two of the state’s three National Weather Service forecast offices are now noticeably understaffed. For the first

For the first time since 1974, no one is on duty during the midnight shift in Fairbanks.

time since 1974, no one is on duty during the midnight shift in Fairbanks. “All the overnight forecasts are now coming out of Anchorage,” some 350 miles away, Thoman explains. Since the area has such varied topography, understanding local weather requires deep, location-specific expertise. “But Anchorage didn’t get new staff. And nobody there has meaningful experience forecasting northern Alaska.”

The result, he says bluntly, is what you’d expect: Less accurate forecasts in a region where precise weather information can be a matter of life and death. “The loss of expertise within NOAA is going to have ramifications far and beyond” the meteorologists who’ve just lost their jobs, he says. “It’s emergency managers, it’s anybody that has relied on briefings from the Weather Service”—meaning anyone who wants to know the next time it’s going to rain. And that institutional knowledge? “That’s gone. And that loss of expertise is not coming back.”

The instability has already taken a toll. Scientists like Sarah Cooley, who once led NOAA’s ocean acidification research, have been caught in a bureaucratic whiplash—fired, reinstated following a court ruling, then fired again after the injunction was overturned. “Who’s going to want to go work for NOAA now?” asks Potemra. Teaching climate science at the University of Hawaii last semester, he watched students wrestle with an impossible question: Should they stick with a career in climate research, or pivot to a less volatile area, as climate science becomes politically targeted?

This uncertainty also impacts the relationships that make international collaborations possible. Potemra has been working with communities in the island archipelago country of Palau to gather data and track climate indicators. This information can help people plan for and work around altered weather, such as consecutive dry days for taro farmers. This spring, he was notified that the three-year project he’d been leading through the University of Hawaii, in collaboration with a project funded by the United Nations Green Climate Fund, had been abruptly canceled. “Unfortunately we just got through compiling what would be needed and useful,” he says.

Not being able to complete the project damages the trust Potemra has built with local communities, who are generally wary of outside researchers arriving with promises and then vanishing. “Frustration number one is not being able to follow through,” Potemra says, adding that he fears the project’s termination reinforces long-standing skepticism rooted in a history of extractive science.

Scientific work often doubles as a form of diplomacy, helping build international connections and trust that can make research—and even business ventures or national security—easier. Potemra, for example, has occasionally been able to smooth over Navy relationships in the vast region, helping facilitate various Department of Defense projects. Losing or damaging these relationships weakens the United States’ global ties and reputation.

TASNUVA ELAHI, WITH IMAGE BY SUNDY PHOTOGRAPHY / SHUTTERSTOCK

That's especially true as weather and climate scientists rely heavily on international data-sharing networks—and NOAA historically has been among the most significant contributors. Other countries, such as India, for example, depend on NOAA's global datasets to strengthen and refine their own weather forecasting systems. And one of the best global records of climate change comes from the Mauna Loa observatory in Hawaii, which has measured carbon dioxide in the atmosphere for 67 years. It, and three other key observatories, are slated to be cut, Potemra notes.

Other monitoring has been scaled back too, as many weather balloons have been grounded. In the northwestern Alaskan town of Kotzebue, Thoman says, balloon launches have been “indefinitely suspended” due to staffing shortages caused by budget cuts, and many other locations around the state have reduced their operations by half. Missing these upper-air observations doesn't just affect local forecasts in Alaska, Thoman says. “It affects every model ingesting that data in the world, everywhere.” Because the atmosphere is always in motion, the sudden lack of balloons in western Alaska “could translate to a bad forecast in Nebraska in five days.” While the impact may be subtle at first, over time, it will also limit how well climate models can assess changes and anticipate tipping points.

WEATHER—OR NOT

The daily ritual of checking the weather forecast has long been made possible by publicly funded NOAA data and analysis. Drastic cuts to the agency are threatening the quality of these reports—which are fed into phone apps and live reports across the country.





STORMS AHEAD But we may not know it. With federal cuts to ocean monitoring systems, the ability to keep tabs on impending storms and trends will recede. That might not concern FEMA’s acting director David Richardson, though. He recently told staff he didn’t know that the U.S. has a hurricane season.

SEVERE WEATHER IS NOT WAITING for federal chaos to calm. As hurricane season progresses, NOAA is reckoning with the damage caused by months of internal upheaval, scrambling to rehire staff for “mission-critical field positions” to meet minimum staffing levels.

The stakes will be measured in the mounting toll of disasters we failed to predict, plan for, or prevent. This year, the Federal Emergency Management Agency has lost more than a third of its staff, along with core programs like the Building Resilient Infrastructure and Communities program, and other mitigation grants that previously helped strengthen infrastructure *before* disasters strike. After FEMA administrator Cameron Hamilton was abruptly fired for testifying against the proposed shutdown of FEMA in May, his replacement,

acting director David Richardson stunned staff by saying he didn’t know the U.S. had a hurricane season. The comment came during a June staff meeting, deepening concerns about the agency’s leadership.

Less than a month later, during flash floods in Texas that killed more than 135 people, the National Weather Service’s San Antonio office was missing the staff member who usually coordinates community response, thanks to the Trump administration’s buy-outs. “It’s a tragic example of the ‘last mile problem,’” Thoman says. FEMA’s response was delayed for days by Homeland Security Secretary Kristi Noem’s cost control measures requiring her personal approval of expenditures.

With funding stripped, state and local governments are left scrambling to fill gaps in disaster preparedness and recovery. Former NOAA scientists warn that

TASNUVA ELAHI, WITH IMAGE BY ENGINEERPHOTOS / SHUTTERSTOCK

Severe weather will not wait for federal chaos to calm.

the loss of flash-flood modeling tools, such as those developed by the National Severe Storms Laboratory, which was recently shut down, will limit the ability to anticipate rapidly developing storms like the one in Texas. And cuts seemingly unrelated to weather are compounding the problem. For example, there is one radio station serving the entire northwest Arctic, where there is frequently no phone or internet service. Since Congress cut NPR funding, the station is now slated to close. If it does, Thoman says, “when you’re out hunting or at fish camp, you’ll be left with nothing but the sky itself to tell you what’s coming.”

Even as disasters surge, the Trump administration is undermining federal investment in the science and systems that could help prevent or mitigate these losses. That’s incredibly expensive: A recent analysis by *Bloomberg Intelligence* found that over the past year, the U.S. has spent approximately \$1 trillion on disaster recovery and other climate-related expenses—far exceeding earlier forecasts.

Though the price of survival is climbing, for now, Thoman is counting his blessings. In July, he heard that the Alaska Center for Climate Assessment and Policy had been given a temporary reprieve: Their funding from the annual budget passed under the Biden administration was granted through August of 2026. There’s broad bipartisan Congressional opposition to the president’s proposal to further cut NOAA’s services, but what might happen next is still up in the air. “It’s better than the alternative,” Thoman says, but “we’ve

seen lots of unilateral decisions by agency heads, and the courts have given the blessing to dismantle stuff in spite of Congressional approval.”

For the moment, Thoman plans to return to the basics—asking not just how to fund his work, but why it matters and who it’s for.

Those questions first crystallized for him during his early days as a weather forecaster in Nome, a small town in Northwest Alaska. “I quickly learned that a ‘nice’ day didn’t hinge on temperature or wind speed. If the sun was shining, it was a good day,” he recalled on a University of Alaska Fairbanks podcast.

That simple reality stuck with him not just because it reflected a different relationship with the environment, but also because it taught him to focus on what matters to the people actually living with the weather. It was about how conditions felt on the ground, and what made life easier or harder for those experiencing it firsthand.

That perspective makes watching the networks of American climate science unravel all the more painful. “It is very difficult,” Thoman says. “Some days it’s like, ‘Why the hell am I doing this?’ And I’m doing it because Alaskans need it, whatever the official policy or the administration is.”

“So I’ll keep on until—until I can’t.” ☺

LOIS PARSHLEY is an award-winning investigative journalist. Follow her work at loisparshley.com.

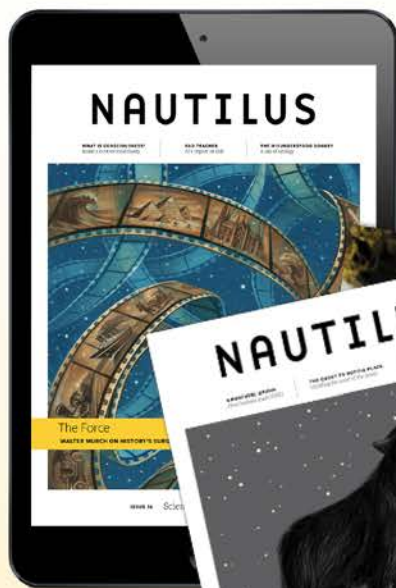
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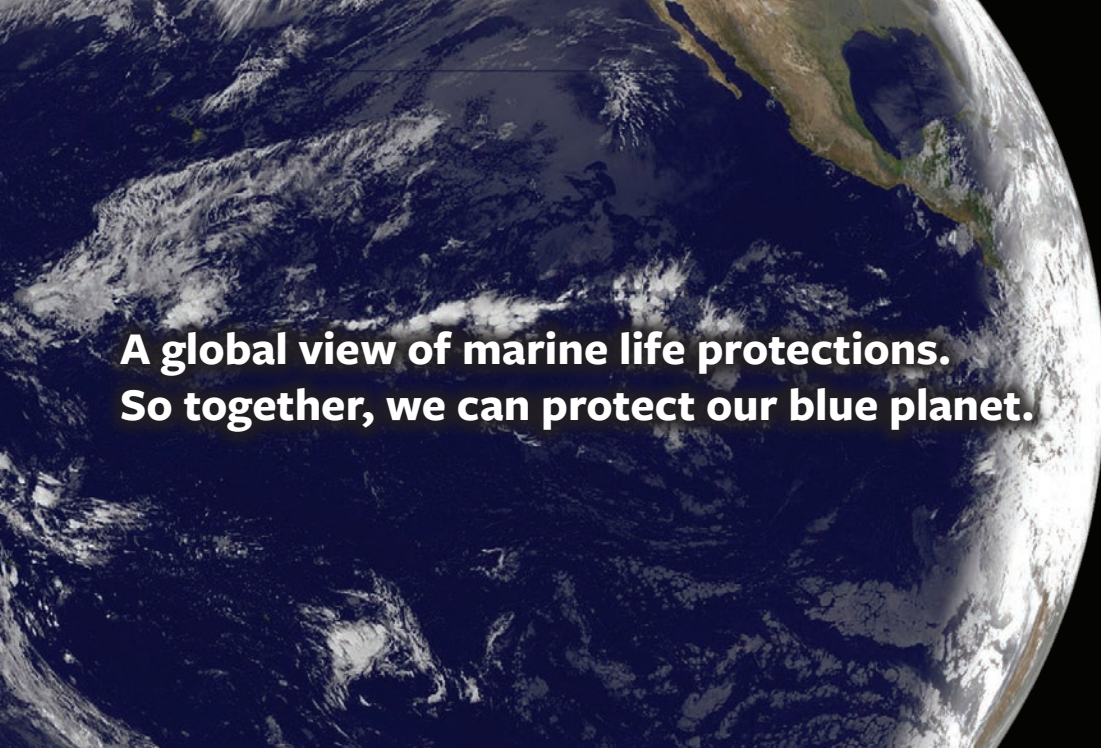


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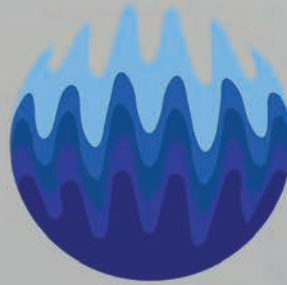
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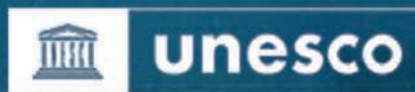


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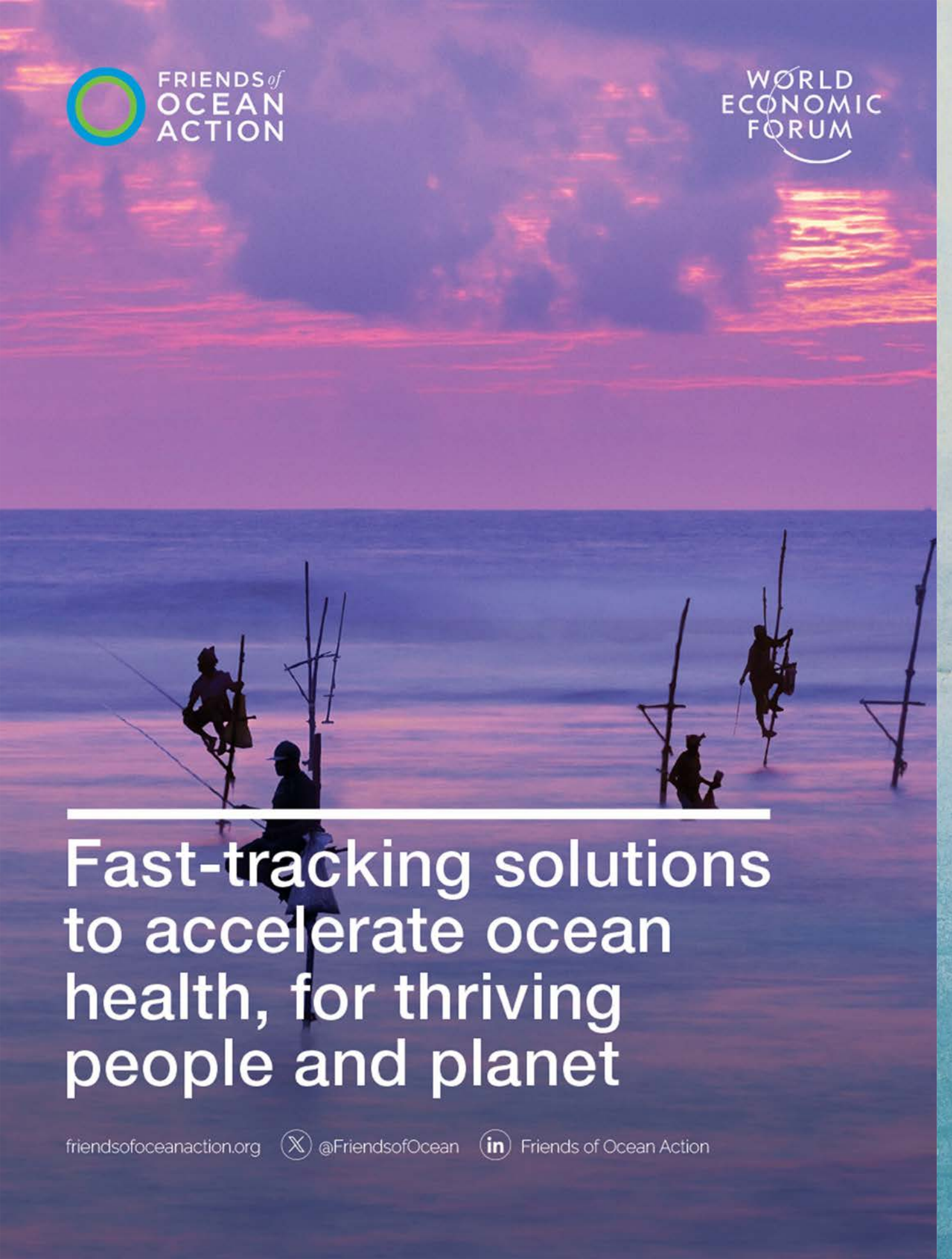
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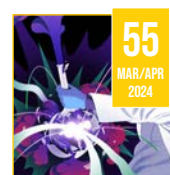
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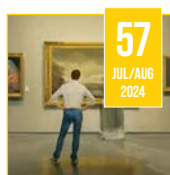
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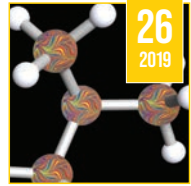
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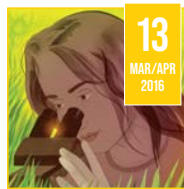
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LAURA POPPICK

The author and journalist on when Earth had no fire

BY LAURA POPPICK



ON FIRE

Fire may seem as inherent to this planet as earth, wind, and water. But while writing *Strata: Stories from Deep Time*, I learned that flames were all but absent here for more than 90 percent of Earth's existence. I had this revelation while researching the rise of oxygen in the atmosphere some 2.4 billion years ago—roughly halfway through Earth's 4.54-billion-year history. I was interested in the arrival of this gas mostly for the ways it influenced life, and how it made possible all of the biological complexity we live amongst today (including, of course, ourselves).

ON OXYGEN

Only once I began trying to place myself in the geologic moment of oxygen's early rise, and imagine what

pre-oxygen days may have looked and felt like, did I realize that an oxygen-free Earth must have also been free of flames. I began digging into the geologic history of fire and connected with Ian Glasspool, a paleobotanist at Colby College who studies the oldest evidence of wildfire on Earth. He confirmed that fire would have been all but absent here until enough oxygen accumulated in the atmosphere to support combustion, and enough kindling sprouted on continents to sustain a flame. This would not have taken place until plants first began growing widespread on land, some 458 million years ago. Lightning strikes may have ignited a microbial mat here or there before this time, but those early flames would have been small and short-lived.

When conditions finally shifted to support sustained wildfires, this new planetary element licked its way through the carbon cycle and became inextricably linked with global climate.

ON DEEP TIME

Any field of science can spark awe and wonder, but I have found that Earth history can go a step further by offering a deep source of solace and grounding. This comfort that I find in the rock record only became deeper and more profound over the years of writing my book *Strata*. When I brought this up with the researchers I interviewed, I often found that they felt similarly.

Immersing myself in deep time and seeing the world through a geologic lens has transformed the way I experience even my most mundane daily activities. When I'm weeding my garden or taking my dog for a walk, I'll remember how new all of this is—the paws trotting down a road, the nose sniffing branches, the hearts beating. I'll remember all that had to happen to make any of this possible—and I'll have a renewed sense of awe and gratitude that we get to be here at all. ☺



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