How Close Are the Planet's Climate Tipping Points?

Earth's warming could trigger sweeping changes in the natural world that would be hard, if not impossible, to reverse.

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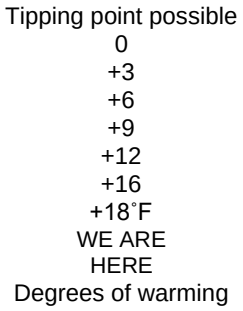
Right now, every moment of every day, we humans are reconfiguring Earth's climate bit by bit. Hotter summers and wetter storms. Higher seas and fiercer wildfires. The steady, upward turn of the dial on a host of threats to our homes, our societies and the environment around us.

We might also be changing the climate in an even bigger way.

For the past two decades, scientists have been raising alarms about great systems in the natural world that warming, caused by carbon emissions, might be pushing toward collapse. These systems are so vast that they can stay somewhat in balance even as temperatures rise. But only to a point.

Once we warm the planet beyond certain levels, this balance might be lost, scientists say. The effects would be sweeping and hard to reverse. Not like the turning of a dial, but the flipping of a switch. One that wouldn't be easily flipped back.

Mass Death of Coral Reefs



SWITCH TO ◦C

When corals go ghostly white, they aren't necessarily dead, and their reefs aren't necessarily gone forever. Too much heat in the water causes the corals to expel the symbiotic algae living inside their tissues. If conditions improve, they can survive this

bleaching. In time, the reefs can bounce back. As the world gets warmer, though, occasional bleaching is becoming regular bleaching. Mild bleaching is becoming severe bleaching.

Scientists' latest predictions are grim. Even if humanity moves swiftly to rein in global warming, 70 percent to 90 percent of today's reef-building corals could die in the coming decades. If we don't, the toll could be 99 percent or more. A reef can look healthy right up until its corals start bleaching and dying. Eventually, it is a graveyard.

This doesn't necessarily mean reef-building corals will go extinct. Hardier ones might endure in pockets. But the vibrant ecosystems these creatures support will be unrecognizable. There is no bouncing back anytime soon, not in the places corals live today, not at any scale.

When it might happen: It could already be underway.

Abrupt Thawing of Permafrost

In the ground beneath the world's cold places, the accumulated remains of long-dead plants and animals contain a lot of carbon, roughly twice the amount that's currently in the atmosphere. As heat, wildfires and rains thaw and destabilize the frozen ground, microbes get to work, converting this carbon into carbon dioxide and methane. These greenhouse gasses worsen the heat and the fire and the rain, which intensifies the thawing.

Like many of these vast, self-propelling shifts in our climate, permafrost thaw is complicated to predict. Large areas have already come unfrozen, in Western Canada, in Alaska, in Siberia. But how quickly the rest of it might defrost, how much that would add to global warming, how much of the carbon might stay trapped down there because the thawing causes new vegetation to sprout up on top of it — all of that is tricky to pin down.

"Because these things are very uncertain, there's a bias toward not talking about it or dismissing the possibility, even," said Tapio Schneider, a climate scientist at the California Institute of Technology. "That, I think, is a mistake," he said. "It's still important to explore the risks, even if the probability of occurrence in the near future is relatively small."

When it might happen: The timing will vary place to place. The effects on global warming could accumulate over a century or more.

Collapse of Greenland Ice

The colossal ice sheets that blanket Earth's poles aren't melting the way an ice cube melts. Because of their sheer bigness and geometric complexity, a host of factors shapes how quickly the ice sheds its bulk and adds to the rising oceans. Among these factors, scientists are particularly concerned about ones that could start feeding on themselves, causing the melting to accelerate in a way that would be very hard to stop.

In Greenland, the issue is elevation. As the surface of the ice loses height, more of it sits at a balmier altitude, exposed to warmer air. That makes it melt even faster.

Scientists know, from geological evidence, that large parts of Greenland have been ice-free before. They also know that the consequences of another great melt could reverberate worldwide, affecting ocean currents and rainfall down into the tropics and beyond.

When it might happen: Irreversible melting could begin this century and unfold over hundreds, even thousands, of years.

Breakup of West Antarctic Ice

At the other end of the world from Greenland, the ice of western Antarctica is threatened less by warm air than by warm water.

Many West Antarctic glaciers flow out to sea, which means their undersides are exposed to constant bathing by ocean currents. As the water warms, these floating ice shelves melt and weaken from below, particularly where they sit on the seafloor. Like a dancer holding a difficult pose, the shelf starts to lose its footing. With less floating ice to hold it back, more ice from the continent's interior would slide into the ocean. Eventually, the ice at the water's edge might fail to support its own weight and crack into pieces.

The West Antarctic ice sheet has probably collapsed before, in Earth's deep past. How close today's ice is to suffering the same fate is something scientists are still trying to figure out.

"If you think about the future of the world's coastlines, 50 percent of the story is going to be the melt of Antarctica," said David Holland, a New York University scientist who studies polar regions. And yet, he said, when it comes to understanding how the continent's ice might break apart, "we are at Day Zero."

When it might happen: As in Greenland, the ice sheet could begin to recede irreversibly in this century.

Sudden Shift in the West African Monsoon

Around 15,000 years ago, the Sahara started turning green. It began when small shifts in Earth's orbit caused North Africa to be sunnier each summer. This warmed the land, causing the winds to shift and draw in more moist air from over the Atlantic. The moisture fell as monsoon rain, which fed grasses and filled lakes, some as large as the Caspian Sea. Animals flourished: elephants, giraffes, ancestral cattle. So did humans, as engravings and rock paintings from the era attest. Only about 5,000 years ago did the region transform back into the harsh desert we know today.

Scientists now understand that the Sahara has flipped several times over the ages between arid and humid, between barren and temperate. They are less sure about how, and whether, the West African monsoon might shift or intensify in response to today's warming. (Despite its name, the region's monsoon unleashes rain over parts of East Africa as well.)

Whatever happens will matter hugely to an area of the world where many people's nutrition and livelihoods depend on the skies.

When it might happen: Hard to predict.

Loss of Amazon Rainforest

Besides being home to hundreds of Indigenous communities, millions of animal and plant species and 400 billion trees; besides containing untold numbers of other living things that have yet to be discovered, named and described; and besides storing an abundance of carbon that might otherwise be warming the planet, the Amazon rainforest plays another big role. It is a living, churning, breathing engine of weather.

The combined exhalations of all those trees give rise to clouds fat with moisture. When this moisture falls, it helps keep the region lush and forested.

Now, though, ranchers and farmers are clearing the trees, and global warming is worsening wildfires and droughts. Scientists worry that once too much more of the forest is gone, this rain machine could break down, causing the rest of the forest to wither and degrade into grassy savanna.

By 2050, as much as half of today's Amazon forest could be at risk of undergoing this kind of degradation, researchers recently estimated.

When it might happen: Will depend on how rapidly people clear, or protect, the remaining forest.

Shutdown of Atlantic Currents

Sweeping across the Atlantic Ocean, from the western coasts of Africa, round through the Caribbean and up toward Europe before heading down again, a colossal loop of seawater sets temperatures and rainfall for a big part of the globe. Saltier, denser water sinks to the ocean depths while fresher, lighter water rises, keeping this conveyor belt turning.

Now, though, Greenland's melting ice is upsetting this balance by infusing the North Atlantic with immense new flows of freshwater. Scientists fear that if the motor slows too much, it could stall, upending weather patterns for billions of people in Europe and the tropics.

Scientists have already seen signs of a slowdown in these currents, which go by an unwieldy name: the Atlantic Meridional Overturning Circulation, or AMOC. The hard part is predicting when a slowdown might become a shutdown. At the moment, our data and records are just too limited, said Niklas Boers, a climate scientist at the Technical University of Munich and the Potsdam Institute for Climate Impact Research.

Already, though, we know enough to be sure about one thing, Dr. Boers said. "With every gram of additional CO2 in the atmosphere, we are increasing the likelihood of tipping events," he said. "The longer we wait" to slash emissions, he said, "the farther we go into dangerous territory."

When it might happen: Very hard to predict.

Methodology

The range of warming levels at which each tipping point might potentially be triggered is from David I. Armstrong McKay et al., Science.

The shaded areas on the maps show the present-day extent of relevant areas for each natural system. They don't necessarily indicate precisely where large-scale changes could occur if a tipping point is reached.