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The Doomsday Glacier

In the farthest reaches of Antarctica, a nightmare scenario of crumbling ice – and rapidly rising seas – could spell disaster for a warming planet.

Dr. Richard Alley, an American geologist, explains the potentially dangerous situation with Thwaites Glacier in West Antarctica.

By Jeff Goodell

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Thwaites Glacier in West Antarctica is so remote that only 28 human beings have ever set foot on it.

Knut Christianson, a 33-year-old glaciologist at the University of Washington, has been there twice. A few years ago, Christianson and a team of seven scientists traveled more than 1,000 miles from McMurdo Station, the main research base in Antarctica, to spend six weeks on Thwaites, traversing along the flat, featureless prairie of snow and ice in six snowmobiles and two Tucker Sno-Cats. "You feel very alone out there," Christianson says. He and his colleagues set up camp at a new spot every few days and drilled holes 300 feet or so into the ice. Then they dropped tubes of nitroglycerin dynamite into these holes and triggered a blast. Sensors tracked vibrations as they shot through the ice and ricocheted off the ground below. By measuring the shape and frequency of these vibrations, Christianson could see the lumps and ridges and even the texture of a crushed continent deeply buried beneath the ice.

But Christianson and his colleagues were not just ice geeks mapping the hidden topography of the planet. They were mapping a future global disaster. As the world warms, determining exactly how quickly ice melts and seas rise may be one of the most important questions of our time. Half the world's population lives within 50 miles of a coastline. Trillions of dollars of real estate is perched on beaches and clustered in low-lying cities like Miami and New York. A long, slow rise of the waters in the coming decades may be manageable. A more abrupt rise would not be.

"If there is going to be a climate catastrophe," says Ohio State glaciologist Ian Howat, "it's probably going to start at Thwaites."

The trouble with Thwaites, which is one of the largest glaciers on the planet, is that it's also what scientists call "a threshold system." That means instead of melting slowly like an ice cube on a summer day, it is more like a house of cards: It's stable until it is pushed too far, then it collapses. When a chunk of ice the size of Pennsylvania falls apart, that's a big problem. It won't happen overnight, but if we don't slow the warming of the planet, it could happen within decades. And its loss will destabilize the rest of the West Antarctic ice, and that will go too. Seas will rise about 10 feet in many parts of the world; in New York and Boston, because of the way gravity pushes water around the planet, the waters will rise even higher, as much as 13 feet. "West Antarctica could do to the coastlines of the world what Hurricane Sandy did in a few hours to New York City," explains Richard

Alley, a geologist at Penn State University and arguably the most respected ice scientist in the world. "Except when the water comes in, it doesn't go away in a few hours – it stays."

With 10 to 13 feet of sea-level rise, most of South Florida is an underwater theme park, including Miami, Fort Lauderdale, Tampa and Mar-a-Lago, President Trump's winter White House in West Palm Beach. In downtown Boston, about the only thing that's not underwater are those nice old houses up on Beacon Hill. In the Bay Area, everything below Highway 101 is gone, including the Googleplex; the Oakland and San Francisco airports are submerged, as is much of downtown below Montgomery Street and the Marina District. Even places that don't seem like they would be in trouble, such as Sacramento, smack in the middle of California, will be partially flooded by the Pacific Ocean swelling up into the Sacramento River. Galveston, Texas; Norfolk, Virginia; and New Orleans will be lost. In Washington, D.C., the shoreline will be just a few hundred yards from the White House.

And that's just the picture in the U.S. The rest of the world will be in as much trouble: Large parts of Shanghai, Bangkok, Jakarta, Lagos and London will be submerged. Egypt's Nile River Delta and much of southern Bangladesh will be underwater. The Marshall Islands and the Maldives will be coral reefs.

Christianson, of course, understands all this as well as anyone. That's why he and others spent many weeks on Thwaites. To understand how fast the ice might slide into the sea, they need to know, among other things, the character of the ground beneath it: Is it slippery bedrock? Is it soft sediments? Are there any hills or mountains beneath the ice, anything that the glacier could cling to in order to slow the retreat? At night, they gathered in the mess tent and ate cookies they had baked in their solar oven and talked about being so far from civilization, and yet in a place where civilization has so much at stake. "We like to think that change happens slowly, especially in a landscape like Antarctica," Christianson tells me. "But we now know that is wrong."

Last summer, then-Secretary of State John Kerry was in Svalbard, an archipelago in the Arctic Ocean off the coast of Norway, visiting glaciers and talking with scientists about the risks of climate change. But it quickly became clear to him that he was in the wrong place. "All the scientists there told me," Kerry says, "if you want to understand what is going on with the climate right now, you have to go to Antarctica." So he did. In November, during the week of the presidential election, Kerry spent three days in Antarctica, the highest-ranking U.S. official to ever visit the continent. He helicoptered around the ice sheets, stopped for a lunch of sauerbraten and spaetzle at a scientific way station called Marble Point, and was briefed about the potential for rapid melting in West Antarctica, especially at Thwaites Glacier. "Scientists are seeing instability rising at a rate that is really alarming," Kerry tells me. "It's mind-blowing what's going on down there."

Antarctica is the size of the United States and Mexico combined, with a permanent population of zero. It is not the territory of any nation, and it has no government, in the conventional sense. Ever since British explorer Robert Falcon Scott and Norwegian Roald Amundson captivated the world with their race to the South Pole in 1911, it has been a playground for scientists and adventurers (and penguins). Seventy percent of the Earth's fresh water is frozen here in ice sheets that can be nearly three miles thick. The continent is roughly divided by the Transantarctic Mountains; East Antarctica is bigger and colder than West Antarctica, which is far more vulnerable to melting, in part because the bases of many glaciers in West Antarctica lie below sea level, making them susceptible to small changes in ocean temperatures.

Until recently, most climate scientists didn't worry too much about Antarctica. It is, after all, the coldest place on Earth, and except for a small part of the Antarctic Peninsula that juts north, it hasn't been warming much. It was also thought to be isolated from the warming oceans by a current that surrounds the continent, essentially walling it off from the rest of the planet. The most recent report by the United Nations' Intergovernmental Panel on Climate Change, which is the gold standard for climate-change science, projected between less than 1 foot and 3.2 feet of global sea-level rise by 2100, with very little of it coming from Antarctica (although the IPCC did include a caveat suggesting that could change).

The IPCC's sea-level-rise projections have long been controversial, partly because the melting of the Greenland and Antarctica ice sheets is so difficult to predict. A few years ago, James Hansen, the godfather of global-warming science, told me that he believed the IPCC estimates were far too conservative and that the waters could rise as much as 10 feet by 2100. For Hansen, the past is prologue. Three million years ago, during the Pliocene Epoch, when the level of CO_2 in the atmosphere was about the same as it is today, and temperatures were only slightly warmer, the seas were at least 20 feet higher. That suggests there is a lot of melting to come before the ice sheets reach a happy equilibrium. Mountain glaciers could contribute a little bit, as would the thermal expansion of the oceans as they warmed, but to get to more than 20 feet of sea-level rise, Greenland and Antarctica would both have to contribute in a big way.

For climate scientists, Greenland was an obvious concern. For one thing, the surrounding Arctic has been warming up faster than any other place on the planet. For another, the melt there was visible to anyone who cared to look: Every summer, as the surface of the ice sheet heats up, water pours off in great blue rivers, some of them falling through holes in the ice called moulins. And compared with Antarctica, Greenland is also easy to get to, just a short flight from Europe to one of the old fishing villages on the coast. You can visit the fastest-moving glacier in the world, the Jakobshavn, and be back at your hotel for a whiskey before dinner.

But in recent years, things have gotten weird in Antarctica. The first alarming event was the sudden collapse, in 2002, of the Larsen B ice shelf, a vast chunk of ice on the Antarctic Peninsula. An ice shelf is like an enormous fingernail that grows off the end of a glacier where it meets the water. The glaciers behind the Larsen B, like many glaciers in both Antarctica and Greenland, are known as "marine-terminating glaciers," because large portions of them lie below sea level. The collapse of ice shelves does not in itself contribute to sea-level rise, since they are already floating (just like ice melting in a glass doesn't raise the level of liquid). But they perform an important role in buttressing, or restraining, the glaciers. After the Larsen B ice shelf vanished, the glaciers that had been behind it started flowing into the sea up to eight times faster than they had before. "It was like, 'Oh, what is going on here?' " says Ted Scambos, lead scientist at the National Snow and Ice Data Center in Boulder, Colorado. "It turns out glaciers are much more responsive than anyone thought."

Luckily, the glaciers behind the Larsen B aren't very big, so sea-level rise wasn't a concern. But the Larsen B prompted scientists to look closer at the ice shelves and movement of glaciers elsewhere in Antarctica. Satellite imagery showed that the ice shelves throughout the continent were thinning, especially in West Antarctica. Some were thinning by a lot. It wasn't clear why, since, unlike Greenland, temperatures in Antarctica weren't warming much, if at all. The only culprit could be the ocean. Scientists figured out that due to changes in the winds and ocean circulation, more deep water was being pushed up under the ice shelves, melting them from below. "Just one degree of change is a big deal to a glacier," says Alley, the Penn State ice scientist.

As it turned out, a lot was going on in Antarctica. The ice shelves were thinning, warmer water was pushing in beneath the glaciers, and the glaciers were flowing faster. The whole place was in dramatic flux. How fast could it go? Nobody knew. Was it possible that the biggest threat to coastal cities wasn't Greenland after all, but Antarctica? If all of Greenland were to melt, that's 22 feet of sea-level rise. If Antarctica goes, it's 200 feet. "Antarctica used to be the sleeping elephant," says Mark Serreze, the head of the National Snow and Ice Data Center. "But now the elephant is stirring."

The 2002 collapse of the Larsen B ice shelf sounded the alarm for scientists. "Antarctica used to be the sleeping elephant," says Mark Serreze, a climate scientist. "Now the elephant is stirring." NASA, MODIS/NASA

The first person to understand the risks that West Antarctica posed in a rapidly warming world was the eccentric Ohio State glaciologist John Mercer. Mercer, who grew up in a small town in England and was known for carrying out his scientific fieldwork in the nude, first visited Antarctica in the mid-1960s. At that time, scientists were just beginning to understand the link between CO_2 emissions and a warming climate. They knew that ice sheets had grown and retreated in the past and caused sea levels to rise dramatically, but the discovery that ice ages were triggered by minor shifts in the Earth's orbit suggested that ice sheets were much more sensitive than anyone thought to small changes in the temperature. Ice cores and improved mapping also helped scientists understand that ice sheets were not monolithic blocks, but in fact made up of rivers of ice, each flowing their own way and at their own rate. In the late 1960s, Mercer may have been the first scientist to ask a question that is still central today: How stable is Antarctica in a climate that is being warmed by fossil-fuel consumption?

Mercer was most interested in West Antarctica. As far as anyone knows, no human had ever set foot on the West Antarctica glaciers until the International Geophysical Year, in 1957, a Cold War collaboration of the U.S. and the Soviet Union and other nations to expand the boundaries of scientific exploration. A team of scientists had trekked across the glaciers of West Antarctica, including Thwaites; by drilling ice cores and taking other measurements, they discovered that the ground beneath the ice was on a reverse slope and had been depressed further by the weight of the glaciers over millions of years. "Think of it as a giant soup bowl filled with ice," says Sridhar Anandakrishnan, an expert in polar glaciology at Penn State University.

In the bowl analogy, the edge of these glaciers – the spot where a glacier leaves the land and begins to float – is perched on the lip of the bowl 1,000 feet or more below sea level. Scientists call that lip the "grounding line." Below the lip, the terrain falls away on a downward slope for hundreds of miles, all the way to the Transantarctic Mountains that divide East and West Antarctica. At the deepest part of the basin, the ice is about two miles thick. In the 1950s, before most scientists understood the risks of global warming, this was considered an interesting insight into the structure of Antarctica, but hardly a discovery of huge consequences.

Then, in 1974, Hans Weertman, a materials scientist at Northwestern University, figured out that these glaciers in West Antarctica were more vulnerable to rapid melting than anyone had previously understood. He coined a term for it: "marine ice-sheet instability." Weertman pointed out that warm ocean water could penetrate the grounding line, melting the ice from below. If the melting continued at a rate that was faster than the glacier grew – which is currently the case – the glacier would slip off the grounding line and begin retreating backward down the slope, like "a ball rolling downhill," says Howat, the Ohio State glaciologist. As the glacier becomes grounded in deeper and deeper water, more of the ice is exposed to warming ocean water, which in turn increases the rate of melt. At the same time, parts of the glacier want to float, which places additional stress on the ice, causing it to fracture. As the face of the glacier collapses, or "calves," more and more ice falls into the sea. The farther the glacier retreats down the slope, the faster the collapse unfolds. Without quite meaning to, Weertman had discovered a mechanism for catastrophic sea-level rise.

Mercer saw that Weertman's breakthrough had big implications. In a 1978 paper called "West Antarctic Ice Sheet and the CO_2Greenhouse Effect: A Threat of Disaster," Mercer focused on the floating ice shelves that buttress the West Antarctica glaciers. Because they are thinner and floating in the ocean, as the water warms they will be the first to go. And when they do, they will not only reduce friction that slows the glaciers' slide into the sea, they will change the balance of the glaciers, causing them to float off the grounding line. And that, in turn, will advance their retreat down the slope. Mercer argued that this whole system was more unstable than even Weertman had realized. "I contend that a major disaster – a rapid [16-foot] rise in sea level, caused by the deglaciation of West Antarctica – may be imminent," he wrote, predicting it would lead to the "submergence of low-lying areas such as much of Florida and the Netherlands." Mercer didn't know how soon this might happen, but when he made his calculations in the mid-1970s, he predicted that if fossil-fuel consumption continued to accelerate, it could begin in 50 years. That is, right about now.

A crack in the Larcen C ice shelf is more than 100 miles long. John Sonntag/NASA

Someday soon – possibly even by the time you read this – a chunk of the Larsen C ice shelf will break off and float into the ocean that surrounds Antarctica. The crack in the Larsen C, which is a close cousin to the Larsen B that broke up in 2002, has been developing for several years. But in the past few months, it has increased dramatically. As I write this, the crack is more than 100 miles long. Such a collapse of ice shelves is exactly what Mercer predicted would be the first sign that disaster is imminent. When it breaks, it will likely be front-page news and cited as evidence that Antarctica is rapidly falling apart.

But it also may not be. "Ice shelves break continually, and sometimes it's not a big deal," says Alley, who was a student at Ohio State when Mercer was a senior professor there. "It will depend a lot on what we see after the shelf breaks off, and how the glaciers in the area react." Alley points out that the glaciers behind the Larsen C shelf are modest, and even if they all accelerated and flowed into the water, it would likely only make a few centimeters' difference in sea-level rise. In other words, this crack-up, in itself, is not what Alley calls an "end-of-the-world screaming hairy disaster conniption fit." But it also doesn't mean that such a disaster isn't underway in West Antarctica on a slightly slower time scale.

Alley is a slight, gnomish man with a beard who keeps a Hula-Hoop in his office and is known for his mean Johnny Cash imitation. When Alley was an undergraduate at Ohio State in the 1970s, he often saw Mercer in the halls and went to a few of his talks. ("I can't confirm whether he practiced science in the nude," Alley says.) He had read Mercer's paper about the risk of Antarctic collapse when it was published in 1978, and it has haunted him ever since. "Did we screw up?" he asked a group of scientists during a talk recently. "I always believed that we would learn enough and be useful enough to society before it was too late. Did we take John Mercer's knowledge and fail to use it?"

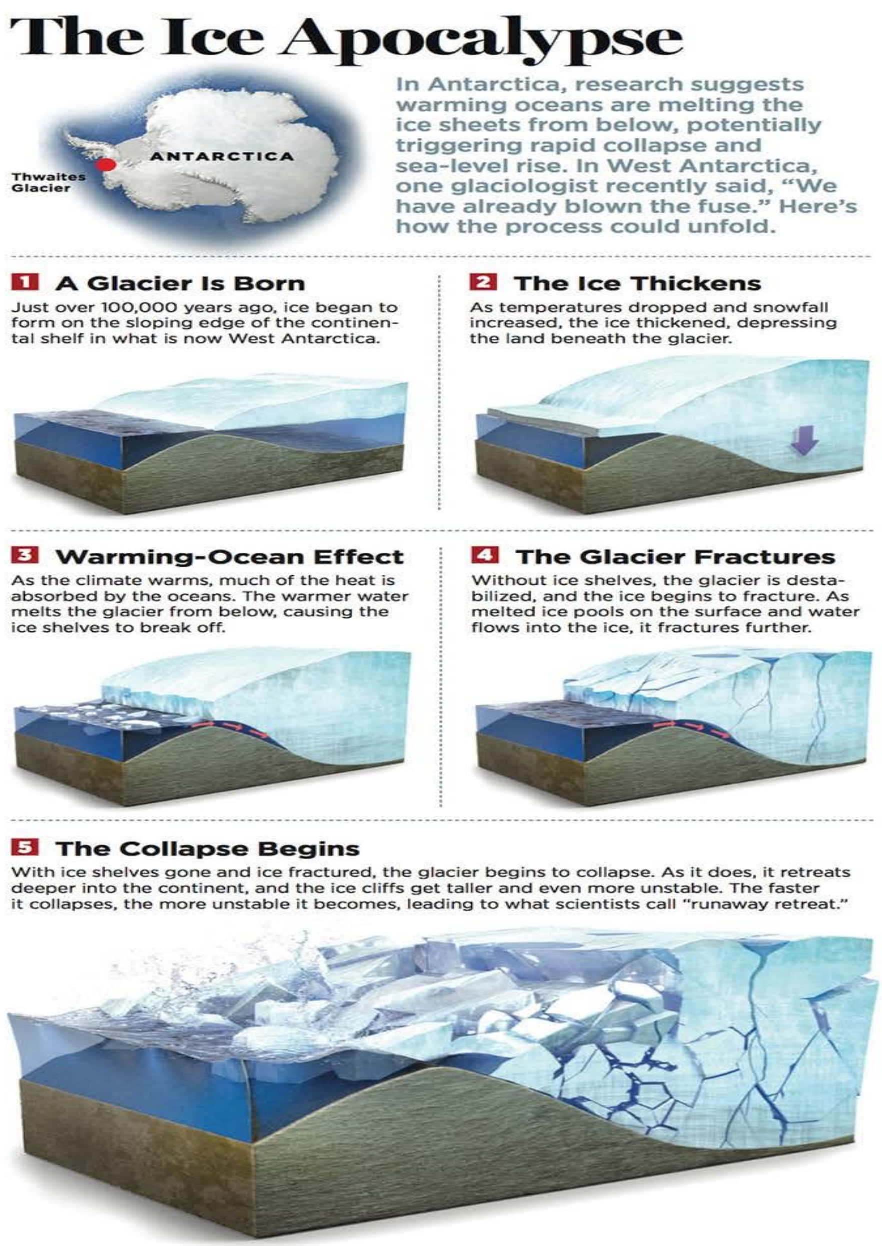

Illustration by Brobel Design

In recent decades, new satellite technology has given scientists a much better view of what is happening in West Antarctica, and most of it has confirmed Mercer's hypothesis. From space, it is possible to measure changes in ice thickness, as well as how fast glaciers like Thwaites are retreating from the grounding line. And the news isn't good. In 2014, two highly respected ice scientists, Eric Rignot at NASA and Ian Joughin at the University of Washington, published separate papers that reached the same conclusion. As Joughin put it, "Our simulations provide strong evidence that the process of marine ice-sheet destabilization is already underway on Thwaites Glacier." In an interview, Rignot was more succinct. In West Antarctica, he said, "we have already blown the fuse."

Alley has spent much of his scientific career thinking about ice dynamics – how ice moves (or doesn't move) when it is pushed, pressured or heated. The collapse of the Larsen B ice shelf in 2002 surprised and worried him, in part because it didn't just break off, as the Larsen C is poised to do – the entire 1,250-square-mile ice shelf disintegrated in a few weeks, going from a nice clean stable ice shelf to a jumble of icebergs in the geological blink of an eye. "Nobody had ever seen anything like that happen before," Alley told me. "As it turns out, a big chunk of ice melts fairly slowly – but it can fracture very, very fast."

After the Larsen B collapse, Alley started thinking more about Mercer's prophecy in West Antarctica, especially as it applied to Thwaites Glacier. He knew that the calving front on Thwaites was about 90 miles long and almost 1,800 feet high – all but 300 feet or so of that was underwater. The pressure of the ocean supported the underwater portion of the glacier, but the rest of it was just a tottering wall of ice that was propped up, for the moment, by ice shelves. And Alley knew that if the glacier retreated into thicker and thicker ice, the calving front would only get higher. How tall, he wondered, could an ice cliff stand before inherent weaknesses in the ice caused it to topple over? Alley knew that by the time Thwaites was fully retreated into the basin, the ice cliffs could theoretically be 6,000 feet high – twice as high as El Capitan, the famous granite face in Yosemite Valley. Imagine mile-high cliffs collapsing into the sea. It is a surreal notion, one that even the most lurid disaster-movie screenwriter would consider implausible. But Alley wondered if such an event *was* possible. And if so, how fast could it happen?

At Thwaites Glacier in West Antarctica, where only 28 human beings have been, glaciologist Kurt Christianson and his team set up camp at a new spot every few days, mapping the topography below the ice along the way. "You feel very alone out there," Christianson says. Courtesy of Kurt Christianson

Like many climate scientists, Alley has long been fascinated by the collapsing ice cliffs on the Jakobshavn Glacier in Greenland. The Jakobshavn is the fastest-moving glacier in the world, sliding into the sea at a rate of about 15 miles per year. If you've seen dramatic images of a calving glacier, such as in the 2012 documentary *Chasing Ice,* it was probably shot at Jakobshavn. A few years ago, while I was reporting another story, I flew along the face in a helicopter. I was struck by how cracked and tortured the sapphire-blue glacier was. I watched a huge chunk collapse into the water. I noticed how it fell straight down, like a trap door had opened beneath it. This was, I now understand, a classic example of ice-cliff collapse. It doesn't topple over. It just implodes.

As Alley knows better than anyone, there are many factors that control how quickly a glacier can slide into the sea, including the amount of friction on the land it is sliding through, as well as how tightly it is buttressed by ice shelves. But another big issue is the strength of the ice itself. There are many differences between the Jakobshavn Glacier and Thwaites. For one thing, Thwaites is many times larger. The calving face of Jakobshavn is only about 10 miles long, versus 90 miles at Thwaites. Also, Thwaites is not constrained in a valley the way that Jakobshavn is, which means there is little friction on the sides to slow it down. If it really gets going, it could collapse much faster than Jakobshavn. More important, Jakobshavn does not sit on the edge of a reverse-slope basin the way Thwaites does. It can calve fast, but it is not what scientists call a threshold system. Thwaites is. But one thing they do have in common is that their structural integrity – and possible future collapse – is dictated by the basic physics of ice.

Standing 300 feet tall, the ice cliffs on the calving face of Jakobshavn are the highest anywhere on the planet. As it happens, there's good reason for that. Alley and other scientists found that ice cliffs on marine-terminating glaciers like Jakobshavn or Thwaites have a structural limit of about 300 feet – after that, they collapse because of stress and weight. So, even if there are sections on Thwaites that are 6,000 feet deep, Alley realized, the structural integrity of ice would never allow a glacier's face to stand that tall. In other words, glaciers with a face up to 300 feet can be relatively stable; after that, forget it. As Alley puts it to me, "It's just collapse, collapse, collapse."

One day, Alley was thinking about a problem that Dave Pollard, a colleague at Penn State, and Rob DeConto, a climate scientist at the University of Massachusetts, Amherst, had been having with their climate model. DeConto and Pollard had been collaborating for years to develop a sophisticated model to help them understand the impact of warming from fossil-fuel pollution on Greenland and Antarctica. Climate models are computer programs that try to capture fundamental physics of the natural world, such as, if the temperature warms one degree, how much will the seas around the world rise? It is not a simple question, and requires calculating everything from changes in how much sunlight the ice reflects to how much one degree of heat causes the Atlantic Ocean to expand. Models have gotten a lot better in the past few decades, but they still can't simulate all the processes in the real world.

One way that scientists test how well a model might predict the future is by seeing how well it recreates the past. If you can run a model backward and it gets things right, then you can run it forward and trust that the results might be accurate. For years, DeConto and Pollard have been trying to get their model to re-create the Pliocene, the era 3 million years ago when the CO_2 levels in the atmosphere were very close to what they are today, except the seas were 20 feet higher. But no matter what knobs they turned, they couldn't get their model to melt the ice sheets fast enough to replicate what the geological record told them had happened. "We knew something was missing from the dynamics of our model," DeConto tells me.

Alley suggested they plug in his new understanding of ice physics, including the structural integrity of the ice itself (or lack thereof), and "see what happens." They did, and lo, their model worked. They were able to get the Pliocene melt just about right. In effect, they found the missing mechanism. Their model was now road-tested for accuracy.

Alley (center) before a congressional committee on climage change. "We are dealing with an event no human has ever witnessed before," he says. Chuck Kennedy/ZUMA

The next thing that DeConto and Pollard did, of course, was run the model forward. What they found was that, in high-emissions scenarios – that is, the track we are on today – instead of virtually zero contribution to sea-level rise from Antarctica by 2100, they got more than three feet, most of it from West Antarctica. If you add in a fairly conservative estimate of the contribution to sea-level rise from Greenland in the same time frame, as well as expansion of the oceans, you get more than six feet – that's double the high-end IPCC scenario.

For anyone living in Miami Beach or Brooklyn or Boston's Back Bay or any other low-lying coastal neighborhood, the difference between three feet of sea-level rise by 2100 and six feet is the difference between a wet but livable city and a submerged city – billions of dollars worth of coastal real estate, not to mention the lives of the 145 million people who live less than three feet above sea level, many of them in poor nations like Bangladesh and Indonesia. The difference between three feet and six feet is the difference between a manageable coastal evacuation and a decades-long refugee disaster. For many Pacific island nations, it is the difference between survival and extinction.

Of course, DeConto and Pollard could be wrong. Or there could be mechanisms they have not considered that might slow down the collapse. Alley wonders if the ice will tumble down so fast that it will create a traffic jam of icebergs in front of it – called a mélange – that will prop up the ice cliffs and keep them from collapsing. Christianson and others are surveying the ground beneath the glacier to see how slippery it is, or to find irregularities in the slope of the bowl that might cause the backsliding glacier to stall for a century or two. DeConto is interested in the firn, the compacted layer of old snow that has not yet turned to ice. "Depending on how it channels meltwater, it could have a big impact on how fast the ice fractures," DeConto says. It could slow it down. But, as DeConto cautions, it could also speed it up. Uncertainty cuts both ways, and once the collapse of West Antarctica begins, it could keep going until the seas have risen as much as 13 feet.

In any case, the threat is clear. In a rational world, awareness of these risks would lead to deep and rapid cuts in carbon pollution to slow the warming, as well as investment in more research in West Antarctica to get a clearer understanding of what is going on. Instead, Americans elected a president who thinks climate change is a hoax, who is hellbent on burning more fossil fuels, who installs the

CEO of the world's largest oil company as secretary of state, who wants to slash climate-science funding and instead spend nearly $70 billion to build a wall at the Mexican border and another $54 billion to beef up the military.

After Kerry returned from Antarctica, we discussed the Trump administration's attacks on climate science, including the decision to strip every mention of climate change from the White House website. "Such a stunningly Luddite moment," Kerry says. "It just underscores the raw, shocking absence of fact from their process. As if to strip the website of something as important as that is somehow going to solve the problem or make it go away is so laughable; it's hard to find the words for it, really. I find that such a huge symbol of a new know-nothingism that is really dangerous for our country, and the world."

In the end, no one can say exactly how much longer the West Antarctica glaciers will remain stable. "We just don't know what the upper boundary is for how fast this can happen," Alley says, sounding a bit spooked. "We are dealing with an event that no human has ever witnessed before. We have no analogue for this." But it is clear that thanks to our 200-year-long fossil-fuel binge, the collapse of West Antarctica is already underway, and every Miami Beach condo owner and Bangladeshi farmer is living at the mercy of ice physics right now. Alley himself would never put it this way, but in West Antarctica, scientists have discovered the engine of catastrophe.