

Too Much Water!

By John Benson

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1. Introduction

If we are talking about the Planet-Earth, the title of this paper is absurd. In general our planet has an almost fixed amount of water. But what isn't static is the water's state. At any given time it may be solid, liquid or gas (water-vapor), and it has a habit of changing from one to the others at all times. This habit is obviously driven by temperature, but it's also driven by many other causes. The deeper you delve into "the water-cycle," the more complex this system becomes. Even though we've been studying this for decades to centuries, fully understanding this still challenges our best climatologists using huge simulation-suites running on our most powerful supercomputers. However we are making progress, and we'd better: a large percentage of people on our planets live in coastal areas and other regions beset by floods. All too soon an increasing percent of these people will get to experience the title of this paper first hand.

I've written about this before – about three years ago I published the two part series, briefly described and linked below:

In Hot Water: This series explores the climate change and the warming of our oceans.

<https://www.energycentral.com/c/ec/hot-water-part-1>

<https://www.energycentral.com/c/ec/hot-water-part-2>

The above two-part post would provide a good context for this post, however, this post will explore immediate threats, specifically how and when sea level will rise. Also, I'm not looking at coastal floods happening centuries in the future, but those for a few decades hence, primarily until 2100. Thus, where we still have time to mitigate the severity.

2. Act 1: The Next Few Years

Everything is too complicated, but we are starting to understand. I've, read much on climate change during the past decade. During this time, climatologists have pretty much agreed where we would get our first significant dose of sea-level rise from.

2.1. Thwaites Glacier

On December 26, 2019, Erin Pettit trudged across a plain of glaring snow and ice, dragging an ice-penetrating radar unit the size of a large suitcase on a red plastic sled behind her. The brittle snow crunched like cornflakes underneath her boots—evidence that it had recently melted and refrozen following a series of warm summer days. Pettit was surveying a part of Antarctica where, until several days before, no other human had ever stepped. A row of red and green nylon flags, flapping in the wind on bamboo poles, extended into the distance, marking a safe route free of hidden, deadly crevasses. The Thwaites Ice Shelf appeared healthy on the surface. But if that were the case, Pettit wouldn't have been there.¹

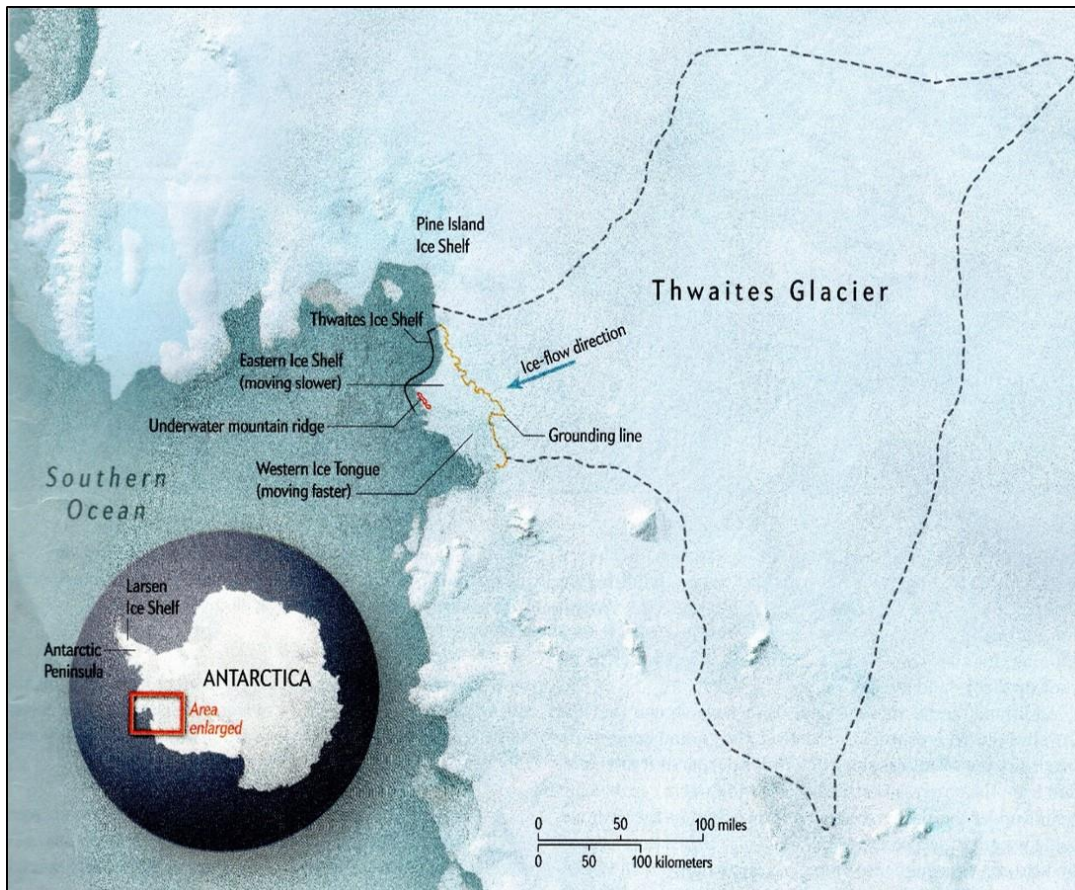
Pettit was studying defects within the ice, akin to hidden cracks in an enormous dam, which will determine when the ice shelf might crumble. When it does, the rest of the

¹ Douglas Fox, Scientific American, "Antarctica's Collapse Could Begin Even Sooner Than Anticipated," Dec 1, 2022, <https://www.scientificamerican.com/article/antarcticas-collapse-could-begin-even-sooner-than-anticipated/>

West Antarctic Ice Sheet behind it could flow right into the ocean, pushing up sea levels around the planet, flooding coastal cities worldwide.

From a distance, the ice shelf looks flat, but as Pettit walked she saw the guide flags ahead of her rise and fall against the horizon—a sign that she was walking across an undulating surface. To Pettit, a glaciologist at Oregon State University in Corvallis, this was significant. It meant that the ice's underside was a rolling landscape—not what anyone expected. In satellite images, the center of the ice shelf looks stable. But it isn't, Pettit says: "There are five or six different ways this thing could fall apart."

The Thwaites Ice Shelf begins where the massive Thwaites Glacier meets the West Antarctic coast. The shelf is a floating slab of ice, several hundred meters thick, extending roughly 50 kilometers into the Southern Ocean, covering between 800 and 1,000 square kilometers. For the past 20 years, as the planet has warmed, scientists using satellites and aerial surveys have been watching the Thwaites Ice Shelf deteriorate. The decline has caused widespread alarm because experts have long viewed the Thwaites Glacier as the most vulnerable part of the larger West Antarctic Ice Sheet. The ice shelf acts as a dam, slowing its parent glacier's flow into the ocean. If the shelf were to fall apart, the glacier's slide into the sea would greatly accelerate. The Thwaites Glacier itself holds enough ice to raise the global sea level by 65 centimeters (about two feet). The loss of the Thwaites Glacier would in turn destabilize much of the rest of the West Antarctic Ice Sheet, with enough ice to raise sea levels by 3.2 meters—more than 10 feet.



Author's comment: The last section of this paper will discuss the immediate sea-level rise (this century). The most important number right now is what is already “baked in” due to our past greenhouse gas emissions, warming and other higher-order effects. Unfortunately the “baked in” number is only vaguely known at present, but consider the following.

Even the most optimistic greenhouse gas emissions scenarios indicate that by 2050 humanity will likely be locked in to at least two meters of sea-level rise in the coming centuries. That will put the homes of at least 10 million people in the U.S. below the high tide line. If the Thwaites Glacier collapses and destabilizes the heart of West Antarctica, then sea-level rise jumps to five meters, placing the homes of at least 20 million U.S. people and another 50 million to 100 million people worldwide below high tide. Although Sacramento, Calif., is not the first city that comes to mind when imagining sea-level rise, it would lose 50 percent of its homes as ocean water pushes 80 kilometers inland through low-lying river deltas. The fate of thousands of coastal towns worldwide hangs on events unfolding in Antarctica right now...

In September 2019, two months before Douglas Fox (primary author) joined Pettit's team as they departed for the frozen continent, they received new satellite images showing two new rifts in the ice shelf. These “daggers” originated where the ice collides with the undersea mountain; the rifts had surged inward toward the coast, to within five kilometers of our planned destination. Expedition leaders worried that one of these rifts could rip through the camp, but the team decided to press forward, with a colleague back home tracking the rifts via satellite. After a series of storms delayed the expedition by a few weeks, we reached the Thwaites Eastern Ice Shelf in mid-December 2019. We assembled a row of tents, protected from the constant easterly winds by walls of snow blocks shoveled and hand-sawed from the landscape, and set up gear for what would be a month of arduous work to come.

As the weather cooled and the snow hardened, Pettit made her first long walks, dragging her radar along preplanned lines. The radar provided two-dimensional profiles of the ice shelf's internal layers, like the slices of a hospital MRI scan. Those first glimpses proved far more interesting than Pettit expected.

Her radar showed that layers in the top 25 meters of the shelf were smooth and mostly flat, but below that they suddenly turned jagged. Pettit speculated that the jagged layers had been part of the ice when it juddered across the rocky coastline bed and started to float seaward, perhaps 15 years before; they were forever imprinted with the trauma of that transition. The smooth layers represented snow that had fallen on top since then, when the ice was afloat.

More surprising, Pettit found that the shelf's underside—a place that human eyes had never seen—looked strangely ordered, as if it had somehow been sculpted intentionally. The underside was corrugated with a series of trenches that ran perpendicular to the direction of ice flow, like waves offshore from a beach. Each trench was 500 to 700 meters wide and cut as far as 50 meters up into the ice, the height of a 12-story building. “These things are huge,” Pettit told me. Oddest of all, the trench walls weren't smooth, as one might expect of melting ice. They were stair-stepped terraces, with a series of vertical walls each five to eight meters tall, like the sides of an open-pit mine. “We don't know what these stepped things are,” she said...

Author's comment: Reference 1 spent much text developing the cause of the above stair-steps. Although this was interesting, I need to conserve some text. The cause was complex water-flow under the ice shelf. Keep reading for the later scientists investigating the above findings (still from reference 1).

On January 11, 2020, researchers at the camp lowered a black-and-yellow cylindrical vehicle, as wide as two hands and 3.5 meters long, by cable into a narrow hole in the ice. Engineers led by Britney Schmidt, a planetary and polar scientist now at Cornell University (then at the Georgia Institute of Technology), had spent eight years developing this remotely operated vehicle, called Icefin. They had driven it under sea ice more than a meter thick and under the edges of two small ice shelves, where it could be winched out by cable if it got stuck. But they had never lowered this precious object through such a massive slab...

Cruising slowly along the shelf's fairly flat underside, Icefin came across a vertical wall cut up into the ice—a stair-stepped terrace like Pettit had seen in her radar traces. And the ice on the terrace walls seemed to be melting far more quickly than the surrounding horizontal underside. In the video, there were blurry ripples in the water, where Icefin's spotlight refracted through gushing eddies of saltwater and freshwater swirling together. Icefin also frequently found dark cracks gaping in the ice—basal crevasses as wide as 100 meters. Schmidt steered Icefin up into several of the crevasses, and there again, she found the water swirling and blurry, suggesting the ice may have been melting quickly.

At the December 2021 American Geophysical Union (AGU) meeting in New Orleans, Schmidt's team presented a careful analysis of Icefin's data, confirming that the vertical ice surfaces are playing a pivotal role in the demise of the Thwaites Ice Shelf. Peter Washam, a research scientist at Cornell, reported that the terrace walls were melting five times more quickly than horizontal ice surfaces, losing 10 or more meters of ice a year. The crevasse walls were melting even more quickly—up to 10 times as fast, losing 20 meters of ice a year. Washam noted that the water currents became turbulent as they encountered these steep surfaces, and this brought water into contact with the ice in ways that more efficiently melted it.

The vertical steps may originate from subtle ups and downs present on the ice's underside when it first pulls up from the bed along the grounding line. The ice might fracture and melt more quickly in these uneven spots, steepening the slope—which increases the melt rate, causing the slope to steepen even more, until it forms a terrace wall that is nearly vertical. As ice melts from these vertical surfaces, the terrace walls migrate horizontally, Scambos says. A basal crevasse that is 10 meters across might widen to 30 or even 50 meters within a year. The melting of the Thwaites Ice Shelf's underside isn't a uniform process; it is highly localized, directed by the topography interacting with currents...

Schmidt's observations may also explain another feature of the terraced trenches Pettit saw near camp. After Pettit returned home, she examined her radar traces and noticed something peculiar: in the highest segment of a trench, she often saw a stack of inverted U-shaped radar reflections—the classic signature of a crevasse penetrating up into the ceiling. This might occur because the thinner ice over a trench sags like a flimsy bridge; as the ice flexes downward, its bulging belly cracks open. This newly formed basal crevasse may pull in warmer water from below. That would cause the walls of the crevasse to melt and migrate outward, widening until its ceiling is broad enough that it

also sags and cracks open—a repeating cycle that could drive cracks ever farther into the ice above.

The massive terraced trenches may have started out as individual basal crevasses, like the ones Schmidt saw eight kilometers upstream at the grounding zone. When Elisabeth Clyne, then a graduate student at Pennsylvania State University, examined radar traces from around the grounding zone, she saw signs that as crevasses moved farther out toward the sea, at roughly 600 meters a year, they were already starting to grow wider and taller through cycles of melting, sagging and cracking. She reported her analysis at the 2021 AGU meeting in New Orleans. Pettit suspects that these trenches may eventually penetrate all the way up through the shelf or at least cut far enough up through the ice that the shelf becomes prone to breaking from other stresses. This process could splinter the shelf into an unsteady mass of giant, shifting shards that will no longer stabilize one of Antarctica's largest glaciers...

Author's comment: I believe the above text and graphic explain why the Thwaites Ice Shelf is accelerating towards the open sea. We have seen other ice shelves disintegrate in West Antarctica, and the disintegration happens pretty quickly (in this case five to 10 years).

Although the Thwaites Glacier will quickly flow to replace the ice shelf, this is “quickly” in terms of glacial flow speeds (maybe 20 to 50 years). Also as the glacier flows it will open up an area under its face for warm ocean water to flow under the glacier, first on the western side, and eventually under whole glacier. Although all of the processes described in this paragraph will happen at “glacial-speed,” the longer this process continues, the more sea-level rise will be baked in.

2.2. Longer Term

Keep in mind that the Thwaites Glacier is just one point-source of sea level rise, albeit one that will certainly start to be felt shortly. There are latterly hundreds of potential point sources, so I'm grouping these into three categories:

Other parts of the Antarctic Ice Sheet: If you wish to research these or the next category, start with the two-part series briefly described and linked in the Introduction. And then use your search engine to identify more recent posts on these potential sources.

The Greenland Ice Sheet: This is important for two reasons:

- 1) The obvious – this is the second largest source of existing and future sea-level rise.
- 2) Melt water from this sheet freshens the North Atlantic, which slows the down-welling of warm, salty water from the surface, which powers the Gulf Stream. These cascading effects have slowed the Gulf Stream (a.k.a. the Atlantic Meridional Overturning Circulation or AMOC). A slowing Gulf Stream traps more warm water around Antarctica, accelerating the breakup of its ice.

Other Glaciers: There are lots of these, and although each of them are tiny compared to the above sheets, collectively they could cause a substantial amount of sea-level rise, and many will melt much faster than the above two sources.

3. Future Sea-Level Rise

Forward-looking coastal cities are already looking at this. Ditto U.S. states and our country as a whole. As a result, NOAA published the source referenced at the end of this paragraph.²

The following text is from the Executive Summary of reference 2.

This report and accompanying datasets from the U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force provide 1) sea level rise scenarios to 2150 by decade that include estimates of vertical land motion and 2) a set of extreme water level probabilities for various heights along the U.S. coastline. These data are available at 1-degree grids along the U.S. coastline and downscaled specifically at NOAA tide-gauge locations. Estimates of flood exposure are assessed using contemporary U.S. coastal flood-severity thresholds for current conditions (e.g., sea levels and infrastructure footprint) and for the next 30 years (out to year 2050), assuming no additional risk reduction measures are enacted.

This effort builds upon the 2017 Task Force report. In particular, the set of global mean sea level rise scenarios from that report are updated and downscaled with output directly from the United Nations Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, through the efforts of the NASA Sea Level Change Team; updates include adjustments to the temporal trajectories and exceedance probabilities of these scenarios based upon end-of-century global temperatures. As with the 2017 report, these global mean sea level rise scenarios are regionalized for the U.S. coastline. In addition, methodology supporting the U.S. Department of Defense Regional Sea Level (DRSL) database¹ (Hall et al., 2016) is adapted for the extreme water level dataset newly developed for this report.

This report will be a key technical input for the Fifth National Climate Assessment (NCA5). These data and information are being incorporated into current and planned agency tools and services, such as NOAA's Sea Level Rise Viewer and Inundation Dashboard,³ NASA's Sea Level Change Portal,⁴ and others. Although the intent of this report is not to provide authoritative guidance or design specifications for a specific project, it is intended to help inform Federal agencies, state and local governments, and stakeholders in coastal communities about current and future sea level rise to help contextualize its effects for decision-making purposes.

Key Message #1: *Multiple lines of evidence provide increased confidence, regardless of the emissions pathway, in a narrower range of projected global, national, and regional sea level rise at 2050 than previously reported.*

- *Both trajectories assessed by extrapolating rates and accelerations estimated from historical tide gauge observations, and model projections, fall within the same range in all cases, giving higher confidence in these relative sea level (RSL; land and ocean height changes) rise amounts by 2050.*

² For a complete list of authors, see front-matter page iii, "Global and Regional Sea Level Rise Scenarios for the United States, National Oceanic and Atmospheric Administration (NOAA), Feb, 2022, <https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report.html>

³ <https://coast.noaa.gov/digitalcoast/tools/slr.html>

⁴ <https://sealevel.nasa.gov/>

- *Relative sea level along the contiguous U.S. (CONUS) coastline is expected to rise on average as much over the next 30 years (0.25–0.30 m (0.8 ft. to 1 ft.) over 2020–2050) as it has over the last 100 years (1920–2020).*
- *Due to processes driving regional changes in sea level, there are similar regional differences in both the modeled scenarios and observation-based extrapolations, with:*
 - *Higher RSL rise along the East (0–5 cm (0-2 in.) higher on average than CONUS)*
 - *Gulf Coasts (10–15 cm (4-6 in) higher)*
 - *West Coast (10–15 cm lower)*
 - *Hawaiian/Caribbean Coasts (5–10 cm lower)*
- *The projections do not include natural year-to-year sea level variability that occurs along U.S. coastlines in response to climatic modes such as the El Niño–Southern Oscillation.*

Key Message #2: *By 2050, the expected relative sea level (RSL) will cause tide and storm surge heights to increase and will lead to a shift in U.S. coastal flood regimes, with major and moderate high tide flood events occurring as frequently as moderate and minor high tide flood events occur today. Without additional risk-reduction measures, U.S. coastal infrastructure, communities, and ecosystems will face significant consequences.*

- *Minor/disruptive high tide flooding (HTF; about 0.55 m (1.8 ft.) above mean higher high water [MHHW]) is projected to increase from a U.S. average frequency of about 3 events/year in 2020 to >10 events/year by 2050.*
- *Moderate/typically damaging HTF (about 0.85 m (2.8 ft.) above MHHW) is projected to increase from a U.S. average frequency of 0.3 events/year in 2020 to about 4 events/year in 2050.*
- *Major/often destructive HTF (about 1.20 m (4 ft.) above MHHW) is projected to increase from a U.S. average frequency of 0.04 events/year in 2020 to 0.2 events/year by 2050.*
- *Across all severities (minor, moderate, major), HTF along the U.S. East and Gulf Coasts will largely continue to occur at or above the national average frequency.*

Key Message #3: *Higher global temperatures increase the chances of higher sea level by the end of the century and beyond. The scenario projections of relative sea level along the contiguous U.S. (CONUS) coastline are about*

- *0.6–2.2 m (2-7 ft.) in 2100 and 0.8–3.9 m (2.6-12.8 ft.) in 2150 (relative to sea level in 2000); these ranges are driven by uncertainty in future emissions pathways and the response of the underlying physical processes.*
- *With an increase in average global temperature of 2°C above preindustrial levels, and not considering the potential contributions from ice-sheet processes with limited agreement (low confidence) among modeling approaches, the probability of*

exceeding 0.5 m (1.6 ft.) rise globally (0.7 m (2.3 ft.) along the CONUS coastline) by 2100 is about 50%. With 3°–5°C of warming under high emissions pathways, this probability rises to >80% to >99%. The probability of exceeding 1 m (3.3 ft.) globally (1.2 m (3.9 ft.) CONUS) by 2100 rises from <5% with 3°C warming to almost 25% with 5°C warming.

- *Considering low-confidence ice-sheet processes and high emissions pathways with warming approaching 5°C, probabilities rise to about 50%, 20%, and 10% of exceeding 1.0 m, 1.5 m (4.9 ft.), or 2.0 m (6.5 ft.) of global rise by 2100, respectively. These processes are unlikely to make significant contributions with 2°C of warming, but how much warming might be required to trigger them is currently unknown.*
- *As a result of improved understanding of the timing of possible large future contributions from ice-sheet loss, the “Extreme” scenario from the 2017 report (2.5 m (8.2 ft.) global mean sea level rise by 2100) is now viewed as less plausible and has been removed. Nevertheless, the potential for increased acceleration in the late 21st century and beyond means that the other high-end scenarios provide pathways that could reach this threshold in the decades immediately following 2100 (and continue rising).*
- *Regionally, the projections are near or higher than the global average in 2100 and 2150 for almost all U.S. coastlines due to the effects from vertical land motion (VLM); gravitational, rotational, and deformational effects due to land ice loss; and ocean circulation changes. Largely due to VLM, RSL projections are lower than the global amounts along the southern Alaska coast and are higher along the Eastern and Western Gulf coastlines.*

Key Message #4: Monitoring the sources of ongoing sea level rise and the processes driving changes in sea level is critical for assessing scenario divergence and tracking the trajectory of observed sea level rise, particularly during the time period when future emissions pathways lead to increased ranges in projected sea level rise.

- *Efforts are under way to narrow the uncertainties in ice-sheet dynamics and future sea level rise amounts in response to increasing greenhouse gas forcing and associated global warming.*
- *Early indicators of changes in sea level rise trajectories can serve to trigger adaptive management plans and are identified through continuous monitoring and assessment of changes in sea level (on global and local scales) and of the key drivers of sea level change that most affect U.S. coastlines, such as ocean heat content, ice-mass loss from Greenland and Antarctica, vertical land motion, and Gulf Stream system changes.*

Final author’s comment: Key Message #1 above is reasonable and actionable information. Above estimates that go beyond 2050, and especially those that go beyond 2100 are probably inaccurate due to the likelihood of additional discoveries in the next few decades greatly clarifying our understanding of the underlying processes for ice sheet and glacier disintegration. However, in addition to pushing this science forward, we also need to seriously work on reducing greenhouse gas emissions.