Glacial ghosts set sea-level trap for East Coast

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The United States has a debt, etched in stone, to pay back to the sea.

Across the world, the oceans are rising. Because of human-caused warming, global sea level has increased at 3 millimeters a year for the past two decades. Sucking in 90 percent of the excess heat trapped by greenhouse gases, the ocean is the world's thermometer, running hot. It's the largest sign, and impact, of climate change.

But as the surge sloshed into New York Harbor last week by Superstorm Sandy made clear, sea-level rise is also a deeply local phenomenon. There is no average ocean. There are only particular coastlines, shaped by geology, currents and gravity. The past matters. And in few places does it matter more than the United States.

Most of the country's eastern coastline is caught at the end of an unstoppable collapse, stemming from the loss of ice sheets many millennia ago. It's a complex process, with one succinct outcome: The ice age set a sea-level trap for the United States. From Massachusetts to the Carolinas, the Eastern Seaboard is sinking.

"[It's] going to experience significantly more sea-level rise than the global average," said Jerry Mitrovica, a geophysicist at Harvard University and expert on the continent's glacial legacy. "The U.S. East Coast could be at double the global average."

This glacial hangover is the most certain reason why the East Coast -- and, over the long term, the West Coast -- can be seen as a hot spot of sea-level rise. There are other, less certain, ways the Atlantic could rush in, too. The massive current that suppresses coastal levels could diminish, though little evidence points to that happening yet. And the ice melt off Greenland, and its gravitational echo, could play havoc with beaches and docks.

And, of course, these regional changes will play out on a stage ever shifting upward, as warming temperatures cause an inexorable rise in global sea levels. Heat expands the ocean, and more land-bound glaciers and ice sheets phase change into the abyss.

"This one sea-level rise number tells us, in a way that nothing else really can, how big an impact we're having on our global environment," said Josh Willis, an oceanographer at NASA's Jet Propulsion Lab. "It's really the one number that says it all."

To be clear, there are limits to what warming-induced ocean rise has done. Sandy would have been devastating without encroaching oceans. It's hard for the signal of a hundred years of sea rise, only some of it due to warming, to stand out from the noise of a 14-foot storm surge, said Tom Cronin, a research geologist at the U.S. Geological Survey.

"Storm surges are separate entities, but they go with the issue of sea level," he said.

As warming continues, the two issues will grow ever more entwined. Like most of the climate sciences, much uncertainty remains in the speed of sea-level rise -- globally, it could go up anywhere from 1 to 4 feet by 2100 -- but none in its ultimate direction.

Over the past few years, particular progress has been made in divining, through satellites, how much of the ocean's added volume is due to melted ice, and how much is due to thermal expansion -- closing the sea-level

"For a while, we were having trouble saying how much was from warming, and how much from melting ice," Willis said. "In a way, that was a great discovery. It forced us to go back and look carefully. ... We've done that. And now the numbers all agree."

That's the present. The future is trickier. Scientists disagree on how much of this meltwater is due to Greenland, Antarctica or mountaintop glaciers. The physics of how ice sheets collapse remains poorly understood. And the natural variability of ocean currents, which can take decades to oscillate, will not give away its secrets easily.

Amid these projections and uncertainties, though, on one area scientists do widely agree.

For the United States, the ice age is bound to make the ocean's return worse.

'Peripheral forebulge'

Press a thumb lightly into an orange, and the glacier's legacy quickly becomes clear.

Millennia ago, the Laurentide Ice Sheet sat heavy across North America, its southeast fringe plunging into New England and New York. The sheet scoured soil, but deeper in the earth, it did more still. Like a finger pressing into a rind, it compressed the rocky, viscous mantle of rock that supports the continent. Beneath the ice, the land fell.

Far from being an unmoving solid, the mantle is viscous; it flows. Under the Laurentide's weight, some mantle compressed and the rest escaped south. Like the bulge encircling an orange-fond thumb, the proto-United States rose up, buoyed by this fugitive rock. The sea had no option but to retreat.

Then, some 12,000 years ago, the big melt began.

Present-day Canada began to rise, its shoulders relieved of a long-burdening millstone. The fugitive mantle returned. And continues to return: Despite global warming, Canada's Hudson Bay is leaving the ocean behind, rising some 4 inches each decade. Hundreds of feet above sea level, ancient lost beaches ring the bay in what geologists used to call emergence curves. It's amazing what taking 3-mile-thick ice off the land will do.

"That region of uplift really covers all areas around the globe that used to be covered by ice," Harvard's Mitrovica said. It includes Scandinavia, Antarctica and Greenland. "All of these regions are presently rebounding upward."

This rebound comes at the expense of the southern, coastal land once shoved upward by the fugitive mantle (the "peripheral forebulge," as geologists call it). From New England to the Carolinas, the shore sank, at an exponential rate, as the mantle retreated. Those rates have fallen off in the past few thousand years, but they have never stopped.

In regions across the mid-Atlantic, smack at the bulge's peak, subsidence remains pronounced. By the most authoritative estimate, Delaware's coast has been falling at 1.7 millimeters a year, a rate more than half the current global sea-level rise. New Jersey falls at 1.4 millimeters; the Hudson River, 1.2 millimeters; Maryland, 1.3 millimeters.

This estimate stems from a recent index of sea-level cores compiled by, among others, Ben Horton and Simon Engelhart at the University of Pennsylvania. Pulling from geological samples taken at 19 sites across the Eastern Seaboard, the team assembled the most accurate current record of glacial subsidence. Starting in Maine

Over the next hundred years, if greenhouse gas emissions don't decline, this sinking will be dwarfed by rising seas. But for the next few decades, it must loom large in the plans of city planners and local experts. Those who do not correct for the ice age effect will see their plans fall short. There is no more certain projection in regional sea-level rise.

Horton's study, however, also carried a surprise. The team compared its index to historical records from tide gauges, crude instruments that have bobbed along on piers, recording the sea's local rhythms, for centuries. And it found that the Laurentide's legacy did not account for all the variation seen up and down eastern shores.

Something else was at play.

Is a key coastal defender weakening?

If there's one thing to know about the ocean, it's this: It does not fill up like a bathtub.

There is no perfect distribution of the fresh water running into the ocean from melting ice. It comes from a calving glacier here, a submerged ice sheet there. Water varies not just in heat, but in height: Hot water stands taller than cold. The world is spinning, and this rotation, along with the sun's incoming energy and subsequent winds, creates currents, whisking water away and changing sea levels.

So if it is a bathtub, it's one with a fidgety scientist in it, NASA's Willis said.

"If I climb in and slosh around, for periods it will be shallow in one end," he said. "The ocean does this on a much bigger scale and much slower scale. ... And it's not just the water sloshing. It's moving around heat."

One of the most important global currents is the Atlantic's meridional overturning circulation, better known as the ocean's "conveyor belt." In simple terms -- the actual current is far more complicated, with elaborate whirls and eddies tied into the winds -- the overturning circulation whisks warm, salty ocean water to the North Atlantic, where it cools, sinks and flows back down the Atlantic's western side, eventually dragging some of that water in a long circuit around the globe.

The circulation does many things, like keep Europe warm, but it does an especially good job of suppressing sea levels on the U.S. Atlantic coast. Its cold waters are dense, lowering the North Atlantic's relative sea level, as a comparison with the higher North Pacific makes clear. If East Coast residents should curse the Laurentide Ice Sheet for accelerating the sea's rise, they should thank the meridional for holding it back.

It's a defense that may weaken soon, however.

Scientists have long believed that warming, or freshwater dumping into the Atlantic from Greenland, could weaken the circulation. Either development could put a snag in the conveyor belt over the next two centuries, boosting sea levels for the East Coast by up to a foot. (On a positive note, though, scientists find it unlikely the circulation could collapse over the same time, putting to sleep one climate tipping-point bugbear.) More than anything else, it's this weakness that has prompted some oceanographers to dub the Eastern Seaboard a potential future hot spot for rising sea levels.

Indeed, several scientists early this year proposed in a prominent paper, published in *Nature Climate Change*, that the circulation is already weakening. But Susan Lozier, an oceanographer at Duke University, disagrees. Scientists have monitored the current since 2004, and their observations do not seem to support the theory, she said.

"Over 100 years, that may be the dominant mechanism. But over five to 10 years, it's not clear."

There's much to understand still about the circulation. (One of Lozier's recent papers is titled "Deconstructing the Conveyor Belt.") The current formerly known as the conveyor belt is deeply tied in with southern winds, which may be as important to its formation as buoyancy. Instead of one continuous current, it could be composed of many, partially connected deep gyres. It seems far from a simple belt.

It's possible that scientists have missed a weakening in the circulation, but there are other possible reasons to account for the East Coast's unexplained sea-level rise. Thermal expansion due to global warming could move in fits and spurts, causing a surge in the south but not the north. There's still much about long-term natural variability scientists don't understand; a wind pattern might shift for decades on part of a coast.

Or it could be water from Greenland, causing its neighbors' seas to rise.

As always with rising seas, it comes back to unknowable Greenland.

Greenland's gravity

The ice sheets of Greenland and Antarctica are one of the durable frustrations for climate scientists, up there with clouds. And they get even knottier for regional sea rise.

In some ways, the ice-sheet community is recovering from its own trap, set in the 1970s. Back then, glaciologists saw how the atmospheric scientists were having success with their global climate models, said Tad Pfeffer, a researcher at the University of Colorado, Boulder. And the ice scientists didn't even have to worry about turbulence.

"That was the only tactic we pursued," he said. "Now we're kind of trapped in that."

Finally, scientists have begun to explore methods beyond one-to-one modeling of the sheets' ice. They are taking inspiration from the world of groundwater modeling, which has long done a good job of projecting its target without simulating every droplet. But the field still suffers from a lack of observations. And it's unclear how much these estimates can be improved before next year's U.N. report.

When it comes to the East Coast, however, Greenland does have one particular twist in store. Its ice-loss legacy does not end with dumping fresh water. Afterward, geography kicks in. The island will rise, undergoing its own post-glacial rebound, just like Canada. (This could mitigate some melting.) But it will also lose something more ephemeral.

It will lose its gravity.

Currently, Greenland is home to so much ice that its huge mass pulls ocean water toward the island, its gravitational pull lifting local sea levels. Like a miniature moon, it creates a permanent tide. But melt enough ice and the ringing water will slough away, circulating back into the Atlantic.

"It's the most counterintuitive effect one could imagine," said Harvard's Mitrovica. "The sea level close to the ice sheet will dramatically drop ... if it's melted enough."

Even with the water it dumps into the ocean, this means that Greenland melt could lower sea levels in a halo some 1,200 miles around it. Newfoundland and Britain, for example, would see their sea levels quickly fall, he

2010, looking at New York City. And by and large, Greenland's gravity loss canceled out much of the rise that would have come from its meltwater.

The community is only beginning to grapple with the importance of gravity to sea levels. These gravitational changes also mean each ice source carries its own geographic signal, its own fingerprint, as Mitrovica calls it. Future sea-level rise will be a mix of thermal inflation, glacial legacies and these fingerprints. Each coastline, each port will be different.

"There's no reason to believe that it should be even," Mitrovica said.

If Superstorm Sandy does in fact turn more U.S. attention to sea-level rise, it will be easy to find all of the uncertainties that complicate the global picture down to the regional level. But few facts about the encroaching ocean are more durable than this: The water humanity adds to the ocean will not easily be stopped, even if all emissions cease.

"Add an inch to the ocean," NASA's Willis said, "and you're not going to get that inch back during my lifetime -- or really during any of our grandchildren's lifetime."