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Meltdown: On the Front Lines of Climate Change

After watching over Earth's poles for decades, NASA aviators see new warnings of the chaos to come.

By Eric Betz

A NASA research plane, the DC-8, flies over the Antarctic Peninsula's northern tip. The aircraft is retrofitted to take measurements of land and sea ice.

"Terrain! Terrain! Pull up!"

The programmed alarm rings throughout the plane's cockpit, announcing a fast-approaching rocky outcrop. Pilot David Fedors casually reaches out a hand and overrides the warning. Twisting the altitude knob to the left, he aims the plane down toward an endless expanse of white, gleaming in the midday sun. He levels it off at a cruising altitude of 1,500 feet.

NASA's Airborne Laboratory is flying low over the West Antarctic Ice Sheet. Inside, a team of scientists is taking the temperature of a continent blanketed in 5 million square miles of ice, equivalent to about 60 percent of the planet's freshwater.

Their instruments are zeroed in on the Amundsen Sea Embayment, a vast region rich in volcanoes, ice shelves and glaciers, some as big as Washington state. Here and across Antarctica, eons of storms have piled snow, inch by inch, layer by layer, until the ice was miles high. Glaciers deliver that ice from the inner reaches of the continent to the ocean, where massive frozen shelves float atop the water.

NASA's crew members navigate the dicey weather and terrain at Earth's poles.

In the belly of the plane, an array of instruments stares at the ice through a window cut into the nearly 50-year-old DC-8's former baggage compartment. Radar signals pass through each ice layer, gauging its depth. Infrared waves measure heat. Laser pulses calculate the surface height. And a gravimeter picks up tiny changes in Earth's gravitational field, perfectly mapping the seafloor's rocky bottom.

These tools reveal what's invisible to the eye. Warm ocean water is washing up and melting the ice from below. Decades of data from the Amundsen Sea Embayment show glaciers are disappearing faster here than anywhere else on Earth. And now, new insights into the terrain suggest the melt is unstoppable. These coastal glaciers hold back inland glaciers, so their collapse would set off a chain reaction ending with the West Antarctic Ice Sheet pouring into the Southern Ocean. That could mean 10 feet of sea level rise. Coastal cities would flood worldwide. But when? This question is the new frontier of climate research.

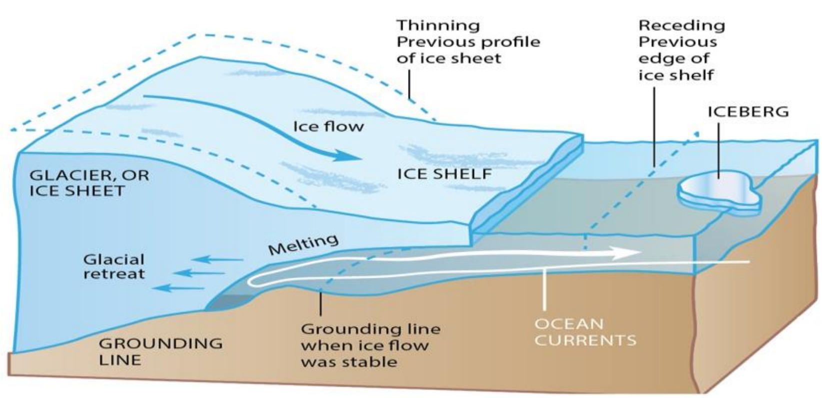
"The big challenge of the future is to figure out these timescales," says Eric Rignot, a glaciologist and professor at the University of California, Irvine. "It may go fast. It may go slow."

Scientists are probing these glaciers from land, air, sea and satellite. And they're plugging that data into cutting-edge computer models. The answers they find — and humanity's response — could forecast the planet's future for millennia.

Mission to Earth

Scientists knew more than a century ago that adding carbon dioxide to our atmosphere would warm temperatures. Yet it was partly observations of another planet altogether that helped launch the effort to understand what was happening on Earth. The first explorations of Venus showed how greenhouse gases trap heat and stifle a planet. James Hansen, now one of the world's most recognized climate scientists, was spearheading NASA's Pioneer mission to Venus in the late 1970s. Astronomers were learning that atmospheric carbon dioxide levels hundreds of times greater than Earth's made our nearest neighbor boiling hot at its surface.

Venus helped call Hansen's attention to the climate problems at home. So he resigned his post and set about reworking a sophisticated weather model into a long-term climate projection. Then, Hansen and his colleagues asked the model a simple question: How would Earth respond if carbon dioxide emissions double? The journal *Science* published the alarming answer in 1981: Regional droughts. Sea level rise. Global warming. Other scientists were reaching similar conclusions.



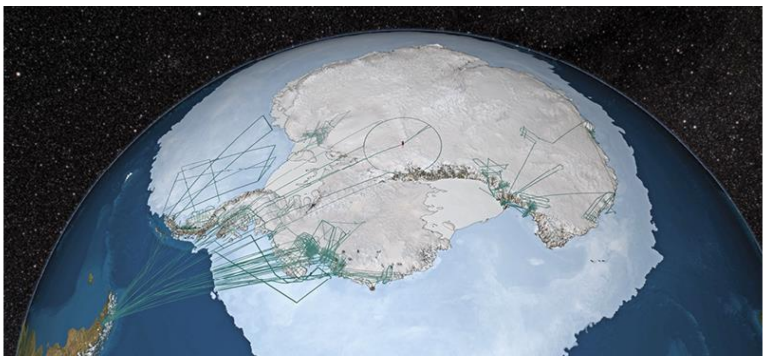
Warm ocean water circulates under ice shelves, melting the glacier's underbelly and pushing the grounding line, where ice meets rock, farther inland. This destabilizes the glacier and quickens its retreat.

“The details have been filled in much better,” Hansen says, “but that 1981 paper had an outline of the problem that we now have thousands of scientists struggling on.”

Amid the fresh scientific questions emerging on Earth — and sweeping budget cuts for space exploration — Congress in 1984 gave NASA a new mandate: increase “human knowledge of the Earth.” By the early 1990s, the space agency was laying the groundwork for what would become the Earth Observing System, its main climate science contribution.

Eventually the space agency deployed a team of scientists and crack flyers, some of them NASA test pilots, to Greenland. They circumnavigated harsh weather and unforgiving terrain until they found the first proof for vanishing ice sheets.

Jim Yungel was an early recruit to this “Mission to Planet Earth.” With the threat that a warmer world would melt glaciers, NASA wanted his group to measure the ocean’s height and track sea level rise. “That’s very difficult to do,” Yungel says. Tides, waves, even large ships make it nearly impossible to detect changes.



Operation IceBridge launches from its home base in Chile. Pilots refer to the crisscrossing flights above West Antarctica to take measurements as “mowing the lawn.”

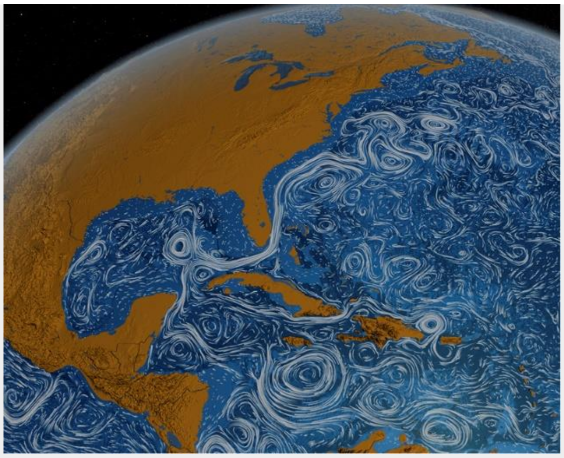
So they’d map Greenland instead. At the time, scientists had hints from satellites, but they weren’t sure if the world’s major ice sheets were melting. GPS was in its infancy. The plan was for NASA pilots to crisscross the continent in jets loaded with new technology that promised precision measurements unlike any made before. “For decades, glaciologists had sort of been toiling in obscurity with small-scale tools,” says NASA’s John Sonntag, a veteran of those early flights and still part of the team.

Test runs over Greenland in the early 1990s showed that the upstart team could measure ice sheet height to within just a few inches. By 1993 and 1994, they were flying scientific grids over the glaciers. “We didn’t know what changes we were looking for, but we thought they’d be pretty small,” Sonntag says. So when the team returned to their flight paths five years later, they were surprised at how fast the coastal glaciers had melted. Greenland was losing 12 cubic miles of ice each year. Their research, published in *Science* in 2000, was the first to measure the shrinking of a major ice sheet. It wouldn’t be the last.

Trouble Below

Unlike in Greenland, it’s typically too cold for ice to melt on Antarctica’s surface. But temperature measurements taken off the continent’s coast found warm water brewing up from the ocean depths. By 1998, satellites revealed that Pine Island Glacier in the Amundsen Sea Embayment was retreating. In the past, experts thought the undersides of glaciers would melt only a few inches each year. This glacier was losing more than 150 feet annually. Pine Island and its neighbor glacier Thwaites both act like a stopper for the West Antarctic Ice Sheet. Scientists worry that their melting might unleash inland floes that would also flood into the sea. “The basic concept is that if these glaciers are going down, the rest of West Antarctica is going down as well,” says Rignot.

In 2002, the NASA team headed south to help with the Antarctic efforts. They hoped to fly 12-hour round trips from the southern tip of South America to the remote reaches of Antarctica. But there were no reliable weather forecasts back then. If they encountered any significant problems, they’d be stuck there — or worse. “It’s very cold, and a long way from any help,” Sonntag says.



Turn Up the Heat

At its core, Earth’s climate system is actually quite simple. Sunlight is most intense in the tropics along the planet’s equator. And physics is constantly trying to push heat from the tropics toward the poles, where it can radiate back to space.

“All the atmospheric circulations that occur, and all the ocean circulations that occur, are basically doing that — they’re transporting heat,” says veteran climatologist Gerald Meehl of the National Center for Atmospheric Research. For example, the Gulf Stream moves heat into the North Atlantic, bringing Europe a pleasant climate, and then it radiates the heat out into space. The poles also have their own currents.

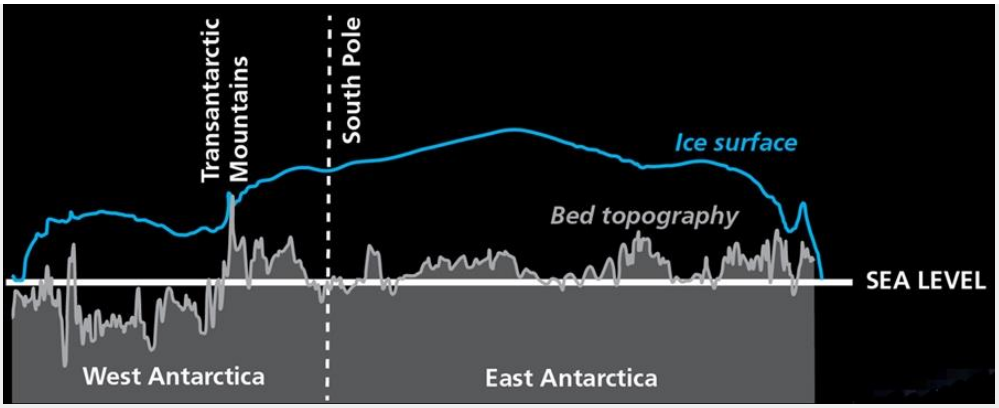
Antarctica’s strong Circumpolar Deep Current circles the entire continent, driven by strong winds called westerlies, which also create the Southern Ocean’s dangerous and choppy waters. Incoming currents drive warm water up from the bottom. In some places, like the Amundsen Sea, the warm water even reaches the continental shelf. And this water is getting warmer.

“All we know so far is that currents are changing. And the waters where those currents come from, those waters are getting warmer,” says Alek Petty, a climatologist on the Operation IceBridge team. “That makes sense with our general ideas of what happens during global warming, but the actual mechanisms are still uncertain.”

“I remember the first flight that we were on,” Rignot recalls. “When we went out there, the winds were actually the opposite [of predictions], and they slowed us down.” It looked like the plane would reach Antarctica and have just enough fuel to fly straight back without collecting any data, proving their mission was truly impossible. “Midway through, the winds changed direction and pushed us through to the Antarctic,” he says. “We gained back everything we had lost.”

Perfect blue skies greeted them. And as they descended toward Pine Island Glacier, 23 excited scientists and technicians crammed into the cockpit to take pictures. “That was an awesome moment,” Rignot says. “We needed measurements from an airplane to measure the thickness of the ice. We can’t do that from space.”

The team’s findings added to glaciologists’ worst fears for the Amundsen Sea Embayment.



East vs. West

Scientists worry about West Antarctica because the ground under its ice sheet sits below sea level. This means that as glaciers recede, warm water quickly rushes in to melt more ice. In the graphic below, the darkest blue regions represent the highest elevations and the white areas represent the lowest on the continent.

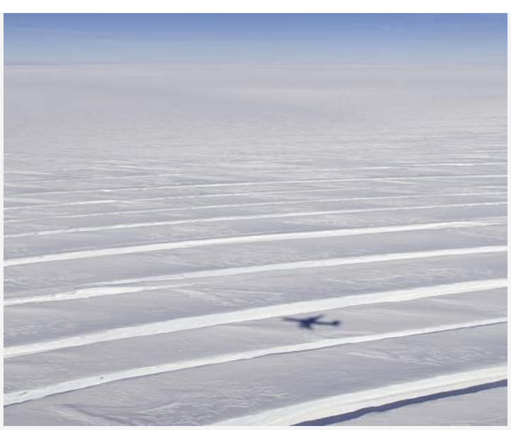
Weak Underbelly

It's tough to tell Earth from sky. As we fly 1,500 feet over West Antarctica, a thin layer of puffy clouds surrounds the aircraft, casting cloud shadows across miles of ice. The team's work environment inside the carved-out DC-8 is far less picturesque. Faded blue upholstery peels around the cockpit windows; the cabin smells like aging vinyl; and computer cables dangle from the overhead compartments. NASA's legacy of airborne climate research lives on in these humble surroundings.

Former Air Force aviators and NASA test pilots fly state-of-the-art scientific instruments up and down the ice sheets on a mission called Operation IceBridge. And this bridge of data is essential: NASA's polar-observing satellite ICESat died in 2009, and the much-delayed launch of ICESat-2 isn't expected until next year.

The aircraft breaks free of the clouds, and a plane-shaped shadow slides across the ice sheet between crevasses more than 100 feet deep. Flying past Pine Island Bay takes the plane over a glacial graveyard. This is where Pine Island and Thwaites meet the sea. Massive ice shelves — Antarctica's largest is bigger than California — get shoved off and float atop the ocean.

The boundary between glacier and ice shelf is called a grounding line. This is "where ice detaches from the ground and starts floating," says Bernd Scheuchl, a UC Irvine climatologist who's mapped ice movements across the continent. "It's the boundary between grounded ice and floating ice."



A series of deep crevasses form as Pine Island Glacier slowly slides toward the sea.

Much of the bottom melt can be blamed on unfortunate topography. East Antarctica's ice sheet hides a mountain range that rivals the Alps. West Antarctica, though, is a different story. Its mile-high glaciers rest on ground that's largely below sea level. Scientists refer to this sunken expanse as the continent's weak underbelly. Scrape off the glaciers, and water will rush in, with just a few islands poking above the ocean surface.

As warm ocean water erodes the bottom of the ice shelf, the grounding line retreats inland. Natural underwater ridges and hills help stabilize a retreating glacier. They act like a brick behind a car tire, stopping a downhill roll. But recent surveys indicate there are hardly any stable ridgelines left to stop the glacial retreat.

Unstoppable Retreat

Over the past 15 years, NASA's airborne team has flown hundreds of zigzag patterns across Pine Island, Thwaites and their neighboring glaciers: Pope, Smith, Haynes and Kohler. Pilots call the crisscrossing flights "mowing the lawn."

Their collected data has allowed Rignot, Scheuchl and their team at UC Irvine to map the seafloor in the region. Satellite data also helped them make a detailed map of grounding lines across Antarctica and determine where glaciers were retreating fastest. "The ocean bed is quite complex, and there are some regions that provide access for warm, deep ocean water to those glaciers," Scheuchl says.

These detailed maps of the landmass under the glaciers show that the retreat can't be stopped. Pine Island, Thwaites and some of their neighbors have used up their stable grounding lines and are retreating miles inland. "There's no big bump inland that could potentially slow down or stop the retreat of these glaciers," Rignot says. "If the ocean gets warmer and warmer, it's going to get faster and faster."

The high-resolution maps have also helped explain how the warm water reaches the undersides of glaciers in the Amundsen Sea Embayment. In a study published in *Geophysical Research Letters* in February, the UC Irvine team used Operation IceBridge data to spot deep channels under the floating ice shelves. Carved by growing glaciers during colder times, these seafloor valleys extend thousands of feet below Pine Island and Thwaites. Other channels reach perhaps more than 5,000 feet deep under the Dotson and Crosson ice shelves, which sit at the mouth of Smith, Pope and Kohler glaciers.

The ice loss is already enough for satellites to detect changes in Earth's gravity field. As the weight of ice sheds and melts into the ocean, the gravity field in the area changes slightly. The European Space Agency's CryoSat mission shows that the continent's volume dropped by 30 cubic miles each year from 2011 to 2014. That data backs up observations from NASA and ESA satellites confirming that the loss was most extreme in the Amundsen Sea region.

Thwaites Invasion

The recent data have stoked fears that Thwaites might pose the biggest threat. Because of the changes already underway here, Thwaites' melting rate doubled in just six years, and it now generates some 10 percent of global sea level rise. The glacier's total collapse could push sea levels 2 feet higher.

Brooke Medley, who was on the flight, studies ice sheets at NASA's Goddard Space Flight Center in Maryland. As the glacier passes by outside the airplane window, she notes that Thwaites could take perhaps 200 years or more to collapse. Already, it's responsible for half the water being added to the ocean along the Amundsen Coast.

“We don’t know how much the ice sheet beneath it is going to melt,” she says. But her team found grim results when they tried to model what might happen. “No matter what scenario we threw at it, Thwaites collapsed,” Medley says.

Scientists aren’t sure how long that will take, and the uncertainty has turned new attention to Thwaites. A deep, narrow trough helps constrain Pine Island Glacier. Thwaites isn’t so lucky. The glacier will widen as it retreats deeper inland. Medley says this geometry means Thwaites will also start to draw more stable ice from neighboring glaciers.

A $25 million expedition next year, funded by the National Science Foundation and the United Kingdom’s Natural Environment Research Council, will collect data on Thwaites that might offer a better expiration date. The field excursion, which scientists are calling “Thwaites invasion,” won’t be easy. The glacier is one of the most hostile places in Antarctica.

Rignot says Operation IceBridge has given his team the data they need to start computing high-resolution models. Their next step is to harness some significant computer power — and pair it with better observations of ocean heat — to try and more precisely forecast sea level rise. “We’ve sort of mapped the heck out of this sector,” Rignot says. “We’ve reached the point now where we have some really nice datasets for the models to run.”

The research from West Antarctica has already prompted the U.S. government to revise its predictions for sea level rise by 2100. A January report by the National Oceanic and Atmospheric Administration reviewed the latest observations from Antarctica and Greenland. It estimated that oceans could rise by 8 feet this century under the worst-case scenario. Their optimistic case: 1 foot. Rignot says the team’s goal isn’t to watch ice sheets collapse. It is to collect evidence so policymakers will listen and take action, even if there’s no way to stop the inevitable.

“We can have an effect on the speed of the retreat of these glaciers,” he says. “If the retreat were to proceed on timescales of 1,000 years instead of a century, it would make a big difference.

The Final Act of Larsen C?

A 70-mile-long crack runs across the Larsen C Ice Shelf on the Antarctic Peninsula.

The narrow and mountainous Antarctic Peninsula extends north from West Antarctica some 800 miles toward Chile. This picturesque region has warmed at least twice as fast as Earth’s overall average. That’s led to the collapse of ice shelves. Larsen A, at the peninsula’s northern tip, crumbled in 1995. By 2002, its neighbor Larsen B collapsed. Both ice shelves were thousands of years old.

Since then, scientists have kept a close watch on Larsen C. It's the biggest ice shelf on the peninsula and the continent's fourth largest. A 70-mile-long crack is currently causing Larsen C to calve a Delaware-sized iceberg into the Southern Ocean. The mammoth iceberg — roughly 10 percent of the entire ice shelf — now dangles like a broken tree limb, tethered by just 12 miles of ice. "A calving event is expected soon," Adrian Luckman of Swansea University said in mid-March. "My guess is days to weeks, but it could be months."

Once this iceberg drifts into the ocean, the shelf behind it might collapse. That's similar to what happened at Larsen B, which will likely disintegrate completely by 2020. However, NASA JPL ice shelf scientist Ala Khazendar cautions that Larsen C's future remains uncertain. Ice shelves naturally shed icebergs, and this ice shelf could recover and avoid the fate of Larsens A and B.

If the floating Larsen C does collapse, it won't raise sea levels directly. But once an ice shelf is gone, the glacier feeding it flows faster to the sea. And that will speed up sea level rise. Beyond that, scientists also worry what the collapse would mean for the rest of the continent as warming continues. "If the fourth-largest ice shelf in Antarctica disintegrates, bigger ice shelves with bigger drainage basins could also be in danger," Khazendar says.

If the West Antarctic Ice Sheet Collapsed…

If the West Antarctic Ice Sheet collapsed, it would cause some 10 feet of sea level rise, and nearly every mile of the southeast U.S. coastline would be inundated. Large regions of Florida and Louisiana would flood.

As the atmosphere warms, heat is transferred to the oceans, which causes water expansion and rising sea levels. Today, Earth's oceans are warmer than they have been in 100,000 years, according to research published in *Science* in January.

Scientists discovered this by using sediment cores from around the world to reconstruct sea surface temperatures from the last interglacial period, which started roughly 129,000 years ago. At that time, temperatures were similar to those from before the Industrial Revolution. The study also showed that 4,000 years later — so, 125,000 years ago — sea surface temperatures had warmed up to nearly match today's readings. That means that, during the interglacial period, it took the planet millennia for a temperature increase that humans managed in just centuries. Alarmingly, sea levels back then were at least 20 feet higher than today's.

The study is just one of a growing number that look at how the Antarctic Ice Sheet behaved in the past and suggest sea level rise could be higher — and come sooner — than scientists expected even a few years ago. Dozens of feet of sea level rise could take millennia, but the latest estimates suggest as much as 8 feet by the end of the century on the extreme end of projections. That timeline is still one of the biggest unknowns.

If Earth is now locked into many feet of ocean rise, it would be enough to flood major metro areas. And the risk to some low-lying areas will rise in mere decades, not centuries. For example, New York City is expected to see regional sea levels rise as much as 30 percent more than the global average. Mud cores pulled from marshes in the city show that the sea level is already rising faster there than at any time in the past 1,500 years, according to research published in the *Holocene Journal* in January. Using their sample site in the Bronx, the scientists found local ocean levels have risen by more than a foot since 1850.

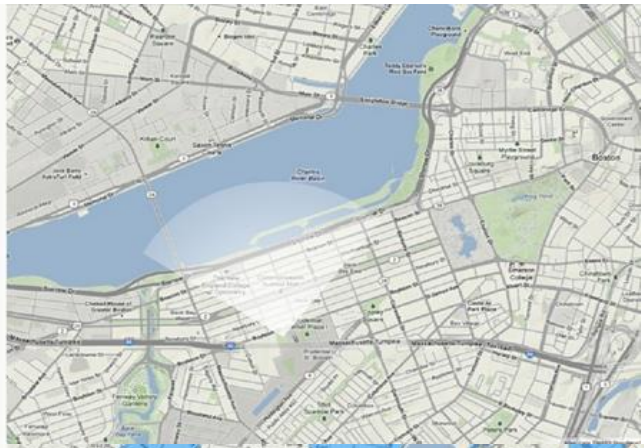
In New York City, studies estimate that adding several more feet of sea level rise would cause some $26 billion in damage and displace nearly 100,000 people by the end of the century.

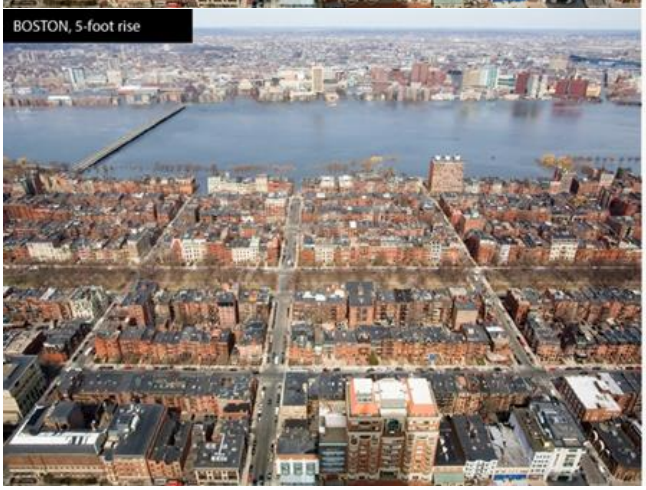
Rising oceans could soak many areas of New York City. Mud cores show that sea level rise is happening in the region faster than at any other time over the past 1,500 years.

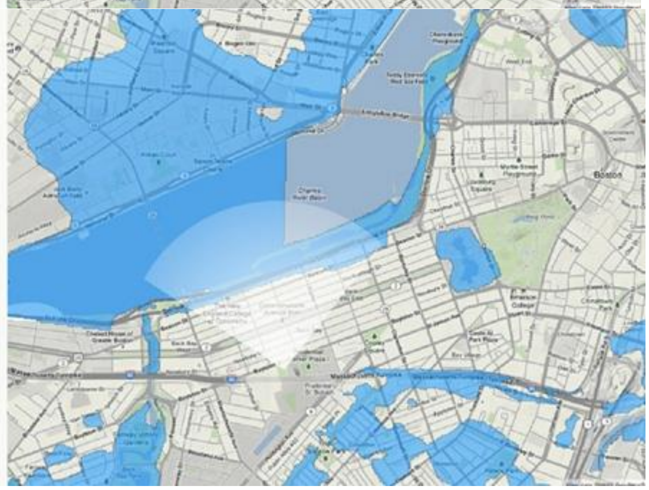
Back Bay's Wake

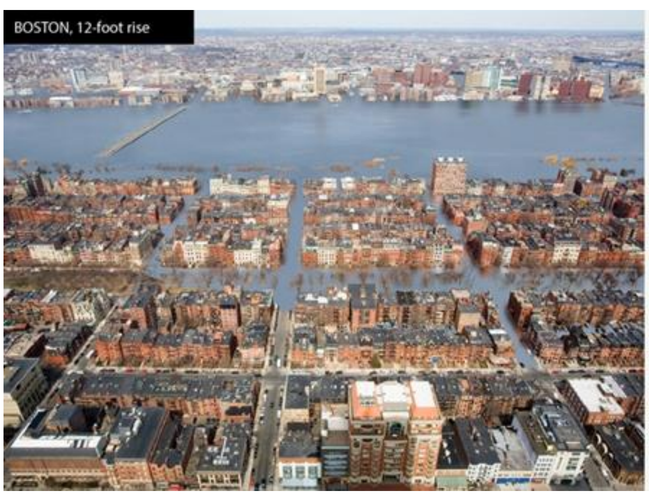
To visualize what rising seas would look like in real life, artist Nikolay Lamm enlisted help from Climate Central scientist Remik Ziemlinski to manipulate images of major cities using the latest science. In the example below, Lamm combined sea level data and topographical flood maps to estimate how high medium tide waters would rise in Boston's Back Bay area. The white cones on the maps indicate the exact location and direction the viewer would be facing. Lamm says his goal was to show people that the places they cherish today might not be there for future generations.


BOSTON, today




BOSTON, 5-foot rise




BOSTON, 12-foot rise