Understanding Sea Level Rise

An in-depth look at three factors contributing to sea level rise along the U.S. East Coast and how scientists are studying the phenomenon

Woods Hole Oceanographic Institution

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Introduction

Sea levels in many areas across the global ocean are rising. Based on early measurements, we know that modern rates of global sea level rise began sometime between the late 19th and early 20th centuries. Since the turn of the 20th century, the seas have risen between six and eight inches globally. New technologies, along with a better understanding of how the oceans, ice sheets, and other components of the climate system interact, have helped scientists identify the factors that contribute to sea level rise.

Global sea level rise is tied to warming air and ocean temperatures, which cause the seas to rise for two reasons. First, they melt ice sheets and glaciers, adding water to the ocean. Second, warmer ocean waters themselves take up more volume due to thermal expansion. Much of the global sea level rise over the last century, due in equal parts to ocean warming and ice melting, is the result of human activity.

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Today, sea level is routinely monitored by tide gauges and satellite altimeters. Tide gauges observe the height of the sea surface relative to a point on land. The National Oceanic and Atmospheric Administration (NOAA) is one of the main agencies in the U.S. that maintains coastal tide gauge measurements and makes them available to the public. Satellite altimeters measure the sea surface height from space with respect to Earth's center of mass. The National Aeronautics and Space Administration (NASA),along with other international space agencies, designs, operates, and maintains satellite altimeters, and makes the data publicly available.

Using data from these two very different observing systems, scientists have concluded that sea level rise is occurring globally.

The seas have not risen at a steady, constant rate. In fact, one study published in the *Proceedings of the National Academy of Sciences* suggests that the rate of global average sea level rise during the 20th century exceeded that of any other century in the last 3,000 years.

The seas are not rising evenly, either. Sea level rise does not occur at the same rate everywhere like a bathtub filling up with water. Rather, the rates at which sea levels rise vary from one place to another due to a number of factors.

This report discusses some of the science of sea level rise and highlights three key processes that contribute to the phenomenon. It also describes some of the research being conducted to better understand how and why sea levels are rising, so that we can more confidently predict future changes. Particular attention is given to the U.S. East Coast, which has been identified by the research community as a sea level rise "hot spot" that is particularly susceptible to the factors discussed here.


Photo: Boston Globe

Since the turn of the 20th century, the seas have risen between six and eight inches globally.

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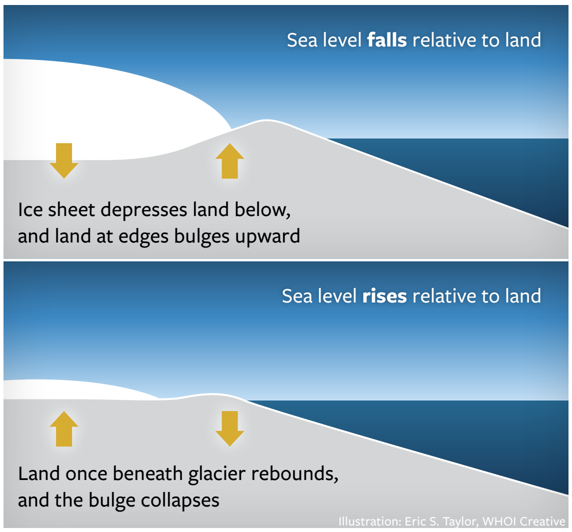
Postglacial rebound

Postglacial rebound—also known as glacial isostatic adjustment—is the planet's ongoing response to the last ice age. While most global sea level rise over the past century has been linked to human activities, this naturally-occurring phenomenon is the main reason why the U.S. East Coast has shown such dramatic regional sea level rise over the last century and the last few millennia. It will continue to be an important factor causing enhanced sea level rise along this coastline for centuries into the future.



Land along a coastline can be submerged when ocean water levels rise. But submergence of that same coastline can also occur if the land is sinking.

IMPACTS OF THE LAURENTIDE ICE SHEET

During the Last Glacial Maximum, which occurred around 26,500 years ago, land areas across much of northern North America were covered by the massive Laurentide Ice Sheet. Like a mattress beneath a slab of concrete, Earth's crust sank beneath the heavy weight of this ice sheet. At the same time, land around its edges—along the U.S. mid-Atlantic coast, for example—bulged up.

As the climate emerged from the last ice age and the Laurentide Ice Sheet melted, the weighed-down areas of the continent gradually starting rebounding and uplifting, while areas on the periphery, including parts of the Eastern Seaboard, started sinking and still are.

Tide gauge readings from along the U.S. Eastern Seaboard show that sea levels rose faster along coastal Virginia and North Carolina during the last century compared with elsewhere along the U.S. East Coast. For example, sea level increased about a foot and a half during the 20th century in coastal communities near Cape Hatteras, North Carolina, while farther north in Portland, Maine, sea level rose only about half a foot over the same time span.

A HOT SPOT FOR SEA LEVEL RISE

To understand why sea level rose so much faster near Cape Hatteras than in Maine, scientists from Woods Hole Oceanographic Institution (WHOI), working with researchers elsewhere, combined observational measurements with geophysical models to give a comprehensive view of the contributors to sea level rise along the East Coast since 1900. They found that glacial isostatic adjustment, combined with the global effects of the warming seas and melting land ice, made parts of the Eastern Seaboard of the U.S. a hot spot of sea level rise in the 20th century.

Maximum extent of the North American ice sheets during the Last Glacial Maximum 20,000 years ago
A reconstruction of the maximum extent of the Laurentide and Cordilleran Ice Sheets, which covered much of North America approximately 20,000 years ago.

Illustration: Eric S. Taylor, WHOI Creative, based on content from NOAA Science on a Sphere

2 Changes to the Atlantic Ocean circulation

Climate models project that a collection of ocean currents in the Atlantic known as the Atlantic Meridional Overturning Circulation (AMOC) will weaken in the future as the climate warms. A slowing of this system of currents is predicted to worsen sea level rise along the U.S. East Coast.

The AMOC—sometimes referred to as the conveyor belt of the ocean—consists of flow near the surface that transports warmer waters northward along with deeper currents that transport cooler waters southward. One limb of the AMOC is the Gulf Stream, which originates in the Gulf of Mexico and flows north just off the shores of eastern Florida, Georgia, and the Carolinas before separating from the coast near Cape Hatteras and meandering into the open North Atlantic Ocean.

Warm waters carried northward by the overturning circulation near the surface eventually reach high-latitude regions like the Norwegian and Labrador Seas. There, they encounter strong winds and cold air temperatures, which cause the ocean to lose heat and those waters to become colder and denser. These cold, dense waters sink into the deep ocean and are then conveyed back southward at depth, creating a circuit.

The Atlantic Meridional Overturning Circulation (AMOC) propels warm surface water to high-latitude regions. There, the water encounters strong winds and cold air temperatures, which causes it to become colder and denser. This cold, dense water sinks into the deep ocean and then is conveyed back southward at depth, creating a conveyor-belt-like loop.

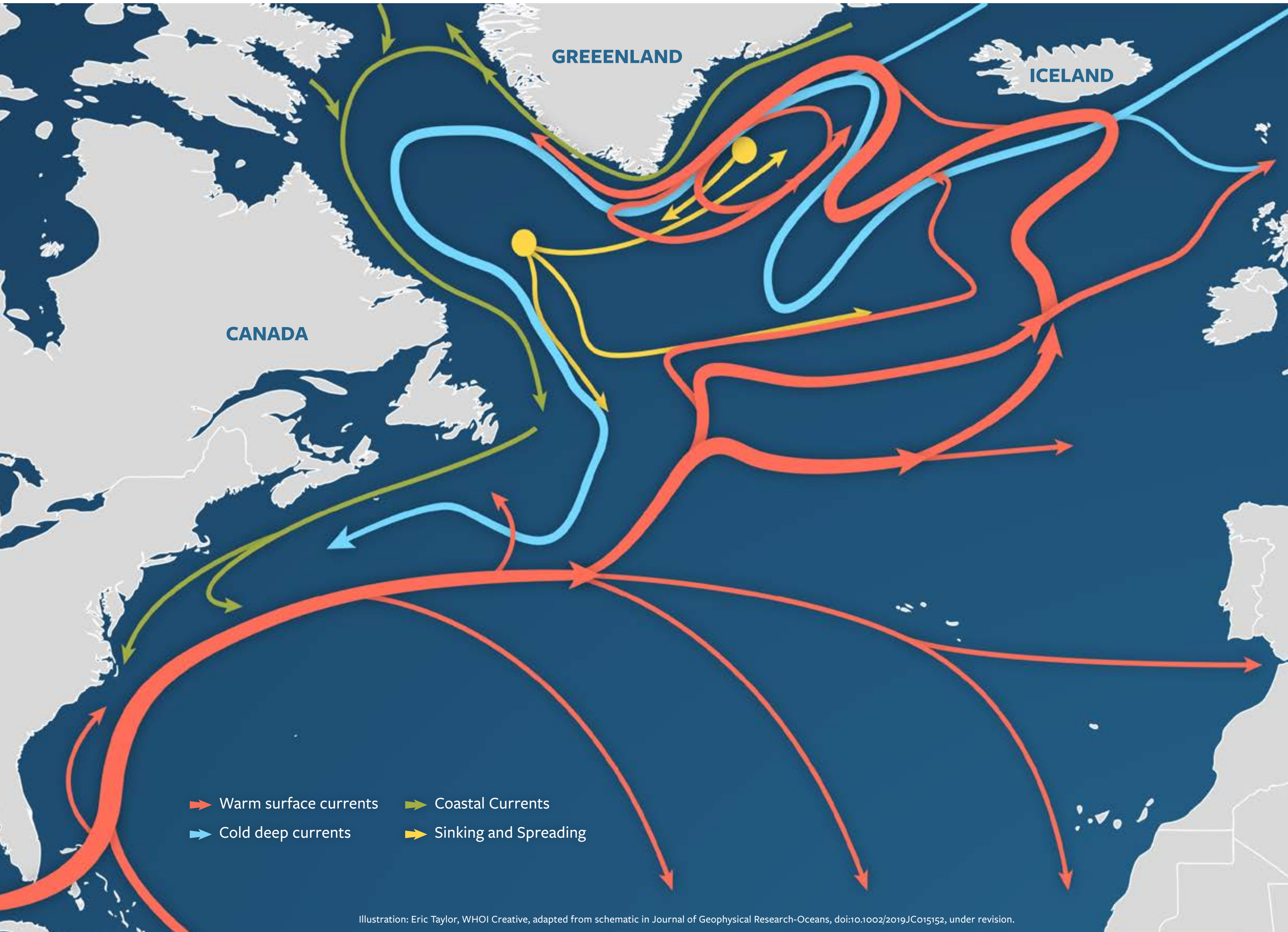


Illustration: Eric Taylor, WHOI Creative, adapted from schematic in Journal of Geophysical Research-Oceans, doi:10.1002/2019JC015152, under revision.

SLOWER AMOC, HIGHER SEAS

Much research has been conducted on the AMOC and how it is being affected by a warming climate and warmer surface waters. Climate models simulating conditions under a warming future climate almost universally project the system to weaken, which would reduce the amount of heat that it brings north in the Atlantic Ocean. Scientists believe it could cause a large-scale redistribution of water in the ocean, which would cause the seas to rise faster on the U.S. East Coast.

To understand how ocean water could be redistributed and lead to sea level rise, it's important to realize that the level of the ocean itself can be higher in some areas and lower in others—sea level isn't "level" at all! There are "hills" and "valleys," just like on land, that are related to ocean currents, Earth's rotation, and the fact that mass is unevenly distributed within the Earth.

Investigating the relationship between sea level and the overturning circulation is difficult, as few continuous observations of the large-scale circulation exist. Long-term records of the Atlantic overturning circulation have only recently become available, and only from a few latitudes. Collecting more data to test model projections is a high priority for oceanographers and climate scientists.

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Photo: iStock.com/thexfilephoto

3 Antarctic Ice Sheet melting

Melting of the Antarctic Ice Sheet has not been a major contributor to sea level rise during the last century. However, given the sheet's enormous mass, and depending on future greenhouse gas emissions, it could become the dominant contributor to sea level rise—along the U.S. East Coast and elsewhere—for centuries into the future.

According to satellite data, nearly twice as much mass has been lost from the Greenland Ice Sheet as from the Antarctic Ice Sheet since the early 2000s. But melting of the Antarctic Ice Sheet could be far more consequential due to its greater mass. To put it into context, if all the ice in Greenland were to melt, global sea levels would rise by about 20 feet on average. If the same were to happen in Antarctica, sea levels would rise by more than 200 feet globally.

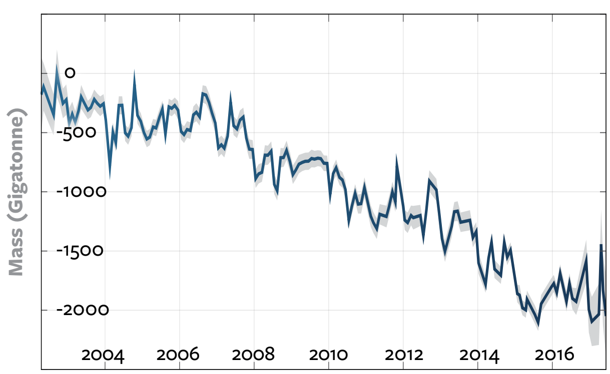
It's also important to recognize that when an ice sheet melts and previously frozen water mass is added to the ocean, the resulting change in sea levels does not occur evenly. In fact, while sea levels rise on average globally, sea level in ocean regions near the former ice sheet actually falls. This counterintuitive behavior results largely from the gravitational attraction associated with water mass.

THE ROLE OF GRAVITY

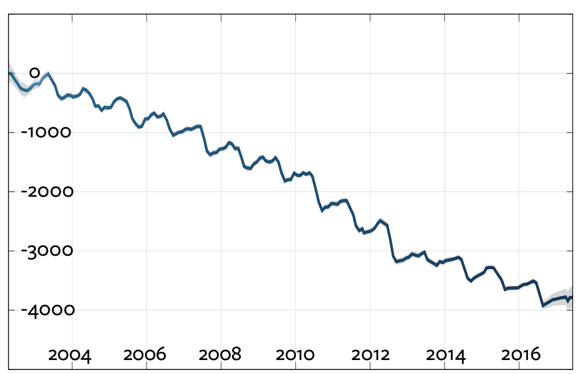
As an ice sheet melts, the water mass that used to make up the ice sheet is no longer locked up on a point of land near the coast. Rather, it is distributed more broadly within the ocean. This reduces the strength of the gravity field at the location of the former ice sheet. Therefore, even though water mass is being added to the ocean due to the melting of the ice sheet, sea levels around where the ice sheet was actually drop.

The change in the gravity field is not a local phenomenon. As the ice sheet melts, an equivalent mass of liquid water is redistributed within the ocean, and the whole planet's gravity field is altered. The result is a complex "fingerprint" of sea level change, with sea level falling in the near field around the former ice sheet and rising more than the global average in the distant far field, where sea level was lower at the start before the ice sheet melted.

ANTARCTICA Direct Measurements May 2002-October 2017



GREENLAND Direct Measurements May 2002-October 2017



Understanding future sea level rise

While scientists have made great strides in understanding how and why sea levels change across space and time, many questions remain. Scientists are actively working to address these knowledge gaps in order to better predict future sea level rise and inform adaptive management efforts, especially for the large number of economically-important cities at high risk for elevated sea levels.

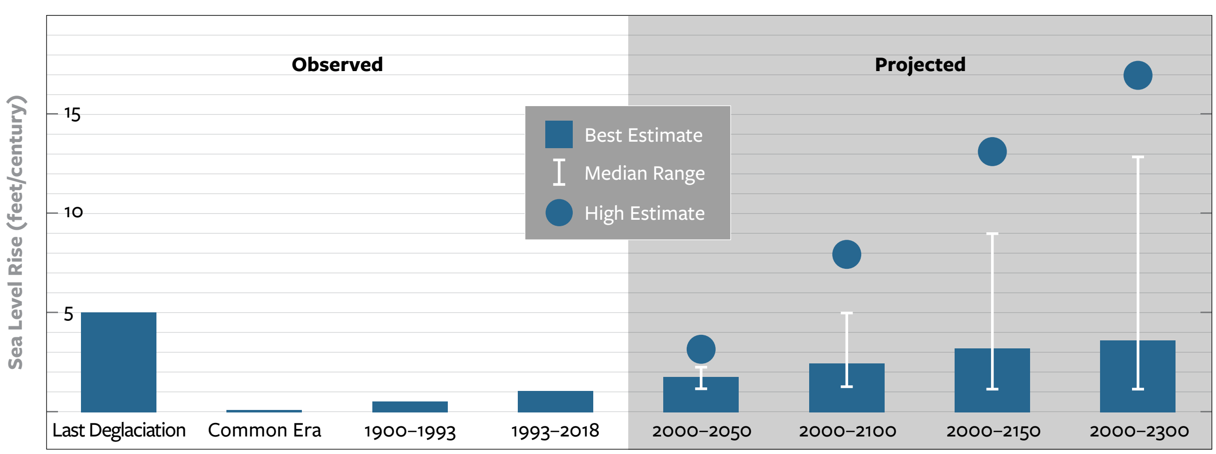
Peer-reviewed studies unanimously predict that global sea level will most likely continue to rise for centuries. Yet, exactly how much the seas will rise in the long term, and how quickly, remains uncertain. Current projections range from one to five feet of global sea level rise between 2000 and 2100, and from three to 38 feet between 2000 and 2300. The uncertainties related to global sea level rise largely hinge on human emissions of greenhouses gases and our evolving understanding of the Antarctic Ice Sheet.

In the near term, most studies predict between eight and twelve inches of global average sea level rise between 2000 and 2050.

MONITORING SEA LEVELS, ICE SHEETS, AND THE GLOBAL OCEAN

Observational efforts are underway to collect more data, and researchers are working to shed more light on important processes that could impact future sea level rise rates. These efforts include new measurement systems designed to continuously monitor the AMOC, such as a collection of ocean sensors known as RAPID that was put in place in April of 2004. This network of sensors measures currents and other water properties across the Atlantic Ocean at N 26°, from Florida to Morocco. Similar to RAPID, the Overturning in the Subpolar North Atlantic Program (OSNAP) began in August 2014 and uses a variety of ocean instruments operating between Canada, Greenland, and Scotland to continuously keep track of the overturning circulation farther north in the North Atlantic. These observing systems are leading to unprecedented new insights into how the overturning circulation changes in time, what causes those changes, and whether future changes might be predicted well in advance.

RECENT PAST AND NEAR-FUTURE SEA LEVEL RISE RATES



Another area of active research is defining how much the Antarctic Ice Sheet will contribute to future sea level rise. Since the early 2000s, satellite observations show that the melting of the Antarctic Ice Sheet contributed only about one-tenth to the rate of global average sea level rise. The majority of the observed sea level rise has been mostly attributed to the melting of smaller mountain glaciers and warming of the global ocean. Yet over that same period, Antarctic Ice Sheet melting accounted for nearly one-half of the global sea level acceleration seen from satellites.

Scientists are currently working to better understand what controls the stability or instability of ice sheets and ice cliffs that are in direct contact with ocean water. These investigations are giving us a better idea of whether the Antarctic Ice Sheet is subject to thresholds or tipping points, and if they have already been crossed.

Scientists are also working to understand how the deep ocean is warming and contributing to global sea level rise. During the last two decades, a network of thousands of floating ocean probes has continuously sampled the ocean's waters, giving unprecedented insight into the unabated warming of the global ocean. However, the ocean is, on average, just over two miles deep, and the current generation of floating probes is able to make measurements only in upper ocean waters shallower than one mile down. This leaves the deep ocean largely unobserved. The only clues scientists have about deep-ocean climate change come from oceanographic cruises, which might sample an ocean basin only a few times over the course of decades due to the high cost of ship time. Scientists are therefore developing a new generation of probes that can withstand the immense pressures of the deep sea to sample the ocean's full volume. In the years to come, these deep probes will provide a comprehensive view of how ocean warming contributes to climate change and sea level rise.

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