NEWS FEATURE

RISING TIDE

RESEARCHERS STRUGGLE TO PROJECT HOW FAST, HOW HIGH AND HOW FAR THE OCEANS WILL RISE.

BY NICOLA JONES

PETE RYAN/NATL GEOGRAPHIC/GETTY

The world's leading climate scientists kicked up a storm in 2007, when they issued their best estimates of how quickly the oceans would swell as the globe warms. The Intergovernmental Panel on Climate Change (IPCC) projected that sea levels would rise by somewhere between 18 and 59 centimetres by the last decade of this century — an upper limit that seemed far too low to other scientists, given the pace of melting in Greenland and other changes. "We were hugely criticized for being too conservative," says Jerry Meehl, a climate modeller at the US National Center for Atmospheric Research in Boulder, Colorado and one of the authors of the IPCC's 2007 report[1].

The panel had previously projected much higher rates of sea-level rise, but its 2007 assessment admitted that it could not tackle the entire problem: the predictions did not include the possibility of rapid changes in ice cover in Greenland or the Antarctic because the authors had concluded that it was impossible to forecast such behaviour with the knowledge and models then available. Yet as early as 2009, it was clear that real sea-level rise was on pace to exceed the 2007 projections[2].

As the IPCC prepares to release its latest summary of climate science next week, researchers say that they now have a better grasp of the problem. Although the final report is not yet complete and the numbers could change, a leaked draft from June forecast a significantly greater rise in sea level — possibly close to 1 metre by 2100. But there is still huge uncertainty over how fast the oceans will rise, how the pattern will vary around the globe and what the ultimate high-water mark will be. Here, *Nature* investigates some of the big questions remaining about sea-level rise.

HOW FAST WILL IT RISE?

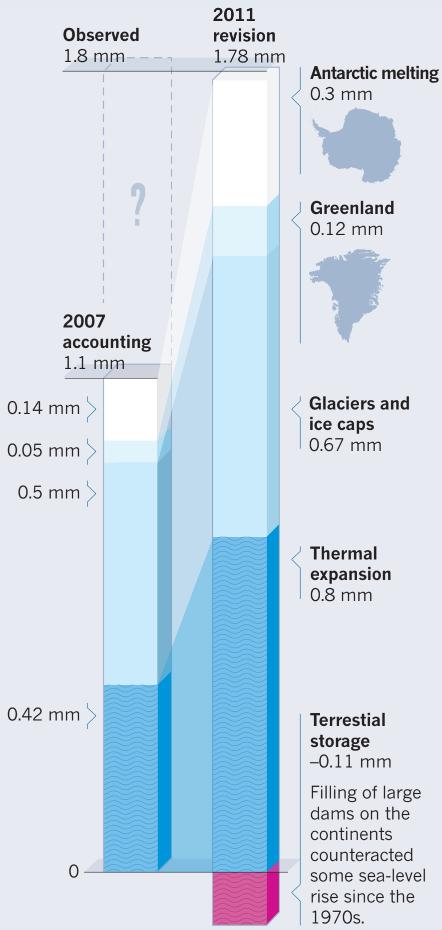
Stefan Rahmstorf, a physical oceanographer at the Potsdam Institute for Climate Impact Research in Germany, is deeply unsatisfied with the standard tools for forecasting sea-level rise: 'process' models that try to represent the physics of every contributing factor. One reason for this discomfort was clear back in 2007. When researchers added up all the individual processes that contributed to rising seas, they could account for only 60% of the observed lift from 1961 to 2003 (see 'Too Much Water'). "The whole was bigger than the sum of its parts," says John Church, co-lead author of the chapter on sea-level rise in the forthcoming IPCC report and an oceanographer at the Australian Commonwealth Scientific and Industrial Research

TOO MUCH WATER

Sea levels have been edging upwards at an accelerated rate over the past decade, and the pace will quicken as the world warms.

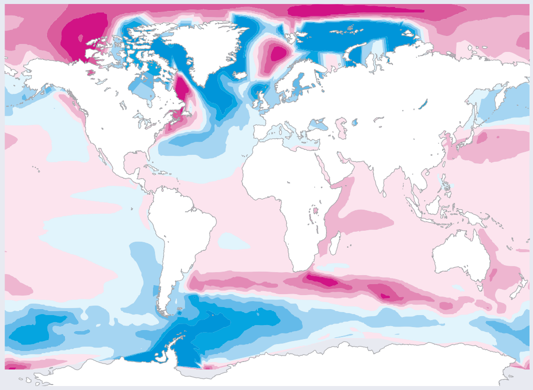
BETTER BUDGET

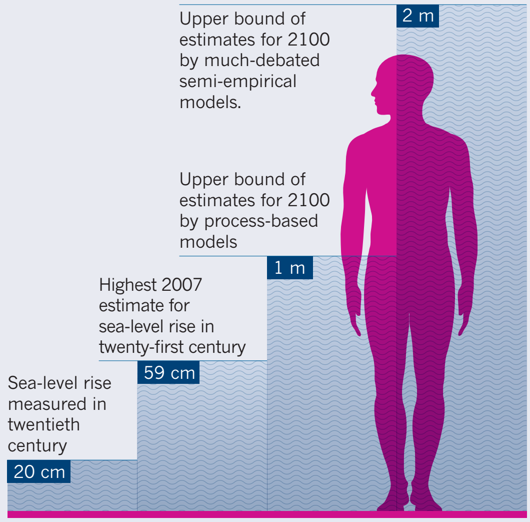
In 2007, researchers could account for only about 60% of the changes in sea level since the 1960s, during a period when the oceans were rising an average of 1.8 millimetres per year. But thanks to improved models, oceanographers can now explain almost all of the changes since the 1970s. Over the past two decades, the rate of rise has picked up, to more than 3 millimetres per year.



HOT SPOTS

For a scenario with an average global sea-level rise of 47 centimetres, local factors will cause the oceans to rise more in some regions and less in others — and even drop in some.





187 million

... people would be swamped by a 2-metre rise in sea levels. That is roughly the combined population of the United Kingdom, Germany and Spain.

SOURCE: 2007 BUDGET: IPCC; 2011 BUDGET: J. A. CHURCH *ET AL. GEOPHYS. RES. LETT.* **38**, L18601 (2011); MAP: REF. 7

Organisation in Hobart. The two biggest effects — the expansion of water as it warms, and the addition of water to the oceans from melting glaciers — each accounted for about one-quarter of the total. A little extra was added in from the melting of the Antarctic and Greenland ice sheets. That left a gaping hole.

So Rahmstorf decided to pursue an entirely different type of model. He looked at the annual rate of sea-level rise from the 1880s onwards, and then matched it with air temperatures at those times. He found a simple relationship: the warmer it got, the faster the sea level rose. In 2007, too late to be considered by that year's IPCC assessment, his model predicted[3] up to 1.4 metres of sea-level rise by 2100 — more than twice the IPCC number.

'Semi-empirical' models such as this have advantages: by definition, they accurately model the rise that has already occurred, and they do not require a full understanding of how and why it is happening. But no one knows how long the relationship at the heart of these models will hold, particularly as melting ice sheets become a bigger factor. The models, says Rahmstorf, "could be good for 50 years, or 100 years. We don't know."

When it comes to making projections, the choice of models has big consequences. Process models generally predict rather less than 1 metre of rise by 2100, whereas semi-empirical models top out at between 1 and 2 metres — enough, at the higher end, to flood the homes of 187 million people. These high-end, semi-empirical estimates are extremely controversial, and the IPCC has low confidence in them. "The only advantage of these models is that they're easy to calculate," says Philippe Huybrechts, an ice modeller at the Brussels Free University. "I think they're wrong."

Process-based modellers have made great progress since 2007, thanks to improved understanding of factors such as how much heat is flowing into the oceans — and thus causing the water to expand — and how much groundwater makes its way into the oceans because of people's unquenchable thirst for fresh water pumped up from below. As a result, modellers can now explain all of the observed rise in sea level, particularly that in recent decades.

But that does not guarantee accurate forecasts. Everyone acknowledges that there are still big issues with process-based projections — in particular, modellers have only a tenuous grasp of how the big ice sheets in Greenland and, especially, the Antarctic might behave and whether they will melt and flow catastrophically into the sea. In all, the ice sheets hold enough water to raise sea levels by more than 65 metres in the long term, compared with as much as 0.4 metres from all the world's glaciers and ice caps.

Despite these problems, the IPCC has decided that researchers finally have a good enough handle on ice behaviour in Greenland and — to a lesser extent — Antarctica to forecast how ice sheets will respond, at least provisionally, says Don Chambers, a sea-level researcher at the University of Texas at Austin. The latest estimates add between 3 and 21 centimetres to the predicted sea-level rise by 2100, although tens of centimetres more are possible, according to the most recent IPCC report draft.

The end result is set to be a much higher forecast for sea-level rise than in 2007. Direct comparisons are difficult because the latest report uses different time frames and emission scenarios, but the leaked draft puts the range of estimates between 28 and 97 centimetres of rise by 2100. That is still not as high as semi-empirical estimates, but process-based results are edging upwards — and the difference is narrowing. "I consider it something of a vindication," says Rahmstorf.

HOW MUCH WILL IT VARY?

When Jeff Freymueller, a geophysicist at the University of Alaska Fairbanks, visited Alaska's Graves Harbor more than a decade ago, his marine charts showed three isolated little islands; what he saw, instead, were three grassy peninsulas connected to the mainland. That was because water levels in some parts of Alaska are dropping — by up to 3 centimetres per year.

The ground there is lifting upwards, in a slow-motion rebound that has been going on for 10,000 years, since the glacial ice sheet that once weighed down the continent receded at the end of the last ice age. Gravitational influences on the oceans are also at work: as local glaciers recede and the Greenland ice sheet melts, their gravitational pull is subtly reduced, allowing more ocean water to slop southwards.

Trends in local sea level can differ strongly from the global average, which is increasing by around 3.2 millimetres per year. "Some places, sea-level rise is ten times faster than the average," says Jerry Mitrovica, a geophysicist at Harvard University in Cambridge, Massachusetts.

One side of this equation is the movement of the land. Canada's Hudson Bay, for example, was once buried under more than 3 kilometres of ice, and the release from that load is now causing the land to rise at about 1 centimetre per year. As that part of North America moves upwards, land to the south is being levered down: the US east coast is dropping by millimetres per year.

Subsidence can cause some areas to sink much faster. Compaction of river sediments and hollowing out of the earth by groundwater extraction, for example, are causing parts of China's Yellow River delta to sink at up to 25 centimetres per year[4].

Adding to the complexity, the oceans do not rise evenly all over the world as water is poured in. Air pressure, winds and currents can shove water in a given ocean to one side: since 1950, for example, a 1,000-kilometre stretch of the US Atlantic coast north of Cape Hatteras in North Carolina has seen the sea rise at 3–4 times the global average rate[5]. In large part, this is because the Gulf Stream and the North Atlantic current, which normally push waters away from that coast, have been weakening, allowing water to slop back onto US shores.

Finally, waters near big chunks of land and ice are literally pulled up onto shores by gravity. As ice sheets melt, the gravitational field weakens and alters the sea level. If Greenland melted enough to raise global seas by an average of 1 metre, for example, the gravitational effect would lower water levels near Greenland by 2.5 metres and raise them by as much as 1.3 metres far away.

Scientists and engineers are only just starting to wrangle all these effects into local projections. In June, the New York City Panel on Climate Change updated its estimates of sea-level rise by including the local effects of gravitational shifts[6]. Panel members concluded that they expect to see 30–60 centimetres of rise by 2050. Finding and combining the right data sets took about six months; the exercise should pave the way for other cities to do the same, says Cynthia Rosenzweig, a climate-impact researcher at NASA's Goddard Institute for Space Studies in New York City. "We really are working to get the best science."

Aimée Slangen, now a member of Church's group in Australia, last year put out one of the first global maps of regional sea-level change that takes all these factors into account, but it had only rough resolution, with pixels of more than 100 kilometres each[7]. Researchers want to provide city-level predictions, but are hampered because these depend heavily on decadal shifts in winds and ocean currents. Predicting such changes is "very problematic", says Chambers.

Regional figures for sea-level rise are of interest not only to people trying to plan for local impacts, but also to those trying to model global effects. For the latter, the numbers bring some good news. Gravitational shifts caused by melting ice in the Antarctic should actually help to prevent catastrophic collapse of the West Antarctic ice sheet: as Antarctica loses some of its ice, local sea levels will fall, which will cause some floating edges of the ice sheet to come to rest on the sea floor. Firmly grounded ice is less susceptible to runaway melting than floating ice. "That's going to stabilize the ice sheet," says Mitrovica.

"SOME PLACES, SEA-LEVEL RISE IS TEN TIMES FASTER THAN THE AVERAGE."

HOW HIGH WILL IT GO?

"Sea-level rise isn't going to stop in 2100," says Church. "I think that's something that people don't really take on board." Eventually, they will. Projections of sea-level rise far into the future jump from tens of centimetres to tens of metres.

For the past few years, Maureen Raymo, a marine geologist at the Lamont-Doherty Earth Observatory in Palisades, New York, has traipsed around abandoned diamond mines in South Africa, visited quarries in Australia and examined road cuts on the east coast of North America, looking for shells and other remnants of beaches from 3 million years ago. She hopes to reconstruct sea levels from the Pliocene epoch, the last time when carbon dioxide concentrations were as high as they are today: about 400 parts per million of the atmospheric volume. That, in turn, should provide a glimpse of what the world might look like in thousands of years, once the planet has had time to react fully to today's emissions.

Current estimates of sea-level rise in the Pliocene range from very little to 40 metres, says Raymo. "But that's not very helpful," she says. The difference between the lower and higher estimates is the difference — crucially — between much of the vast East Antarctic ice sheet melting and staying frozen. Whether or not it melted in the Pliocene, in turn, provides insight for modellers who are trying to work out whether — and how fast — ice sheets might collapse in the next few hundred years.

The trick to pinning this down is not just finding Pliocene beaches, but also working out how the land has moved since they were laid down, as a result of both rebound from the loss of ice sheets and the ongoing movement of mantle rock under the continents. To estimate how such processes have played out over millions of years, researchers rely on models of how much ice covered the continents and how viscous the mantle is — factors that are subject to extreme debate. "Today's models all assume a viscosity of the mantle that is untestable, highly controversial and differs between groups," says Raymo.

This motion of Earth makes a big difference in estimating past events. Previous work, for example, in Bermuda and the Bahamas hinted that the coastline there was 20 metres higher than it is today during a warm period 400,000 years ago. In 2012, however, Raymo and Mitrovica calculated how the ground there had moved — and concluded[8] that half of the apparent sea-level rise was attributable not to rising waters but to sinking land, cutting the sea-level-rise estimate in half.

Given the large error bars, the only way to pinpoint Pliocene sea levels is to get data from many sites and to calculate one best-fit answer for global sea level. Raymo and her team have so far surveyed thousands of kilometres of coast, gathering evidence from dozens of beach sites. She says she needs perhaps eight more locations and five years to finish the job.

But, she admits, whatever she finds will not be a worst-case scenario because greenhouse-gas concentrations are already climbing beyond where they were in the Pliocene. "The real worst-case scenario is we don't limit fossil-fuel combustion," she says. "Then it's 'Hello Eocene'" — returning to a world akin to a warm period 55 million years ago, with maybe just a trace of ice at the poles.

Nearly 70 metres of sea-level rise would drown all of Florida and much of Brazil, and swamp the Statue of Liberty up to her waist. But that might not happen until so many thousands of years from now that humanity has time to adapt — even if that means surrendering much of the land to the waves. ■

Nicola Jones *is a freelance writer near Vancouver, Canada.*

1. Solomon, S. *et al.* (eds) *Climate Change 2007: The Physical Science Basis* (Cambridge Univ. Press, 2007).
2. Allison, I. *et al. The Cophenhagen Diagnosis 2009* (Univ. New South Wales Climate Change Research Centre, 2009).
3. Rahmstorf, S. *Science* **315,** 368–370 (2007).
4. Higgins, S., Overeem, I., Tanaka, A. & Syvitski, J. P. M. *Geophys. Res. Let.* **40,** 3898–3902 (2013).
5. Sallenger, A. H. Jr, Doran, K. S. & Howd, P. A. *Nature Clim. Change* **2,** 884–888 (2012).
6. New York City Panel on Climate Change *Climate Risk Information 2013* (City of New York Special Initiative on Rebuilding and Resiliancy, 2013).
7. Slangen, A. B. A., Katsman, C. A., van de Wal, R. S. W., Vermeersen, L. L. A. & Riva, R. E. M. *Clim. Dynam.* **38,** 1191–1209 (2012).
8. Raymo, M. E. & Mitrovica, J. X. *Nature* **483,** 453–456 (2012).