Where melting ice means retreating seas

By Stephen Battersby

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It sounds impossible but it's true. The sea level around a melting ice cap will fall even as distant shores are inundated.

SIT yourself down on the chilly shore of Greenland. Set your time machine to fast-forward through the next few centuries, and watch as the great ice sheet above you slowly melts and spills into the sea. So far, so predictable. But what happens as all this meltwater pours into the sea may surprise you. While faraway cities battle rising waters, you find yourself high and dry, looking down at the retreating waves. "At your feet, sea level will fall by 100 metres," says geophysicist Jerry Mitrovica. "It's crazy. Crazy but true."

If all Greenland's ice melts, local sea level will fall by 100 metres (Image: Alban Kakulya/Panos Pictures)

How is that possible? It is all to do with the fact that the sea is not as flat as it looks from a distance. Instead of being as level as a bathtub of still water, its surface is marked by watery hills and valleys. They are invisible to our eyes because the slopes are so gradual, but they can be many metres high or deep.

This waterscape has remained essentially the same for the past few thousand years, but now it is beginning to change. As the ice sheets melt, there will not only be more water in the oceans, but the positions of those hills and valleys will shift. Depending on what happens, Boston and New York might face the threat of a new summit in the sea. Or the waves could retreat from Scotland to expose new land.

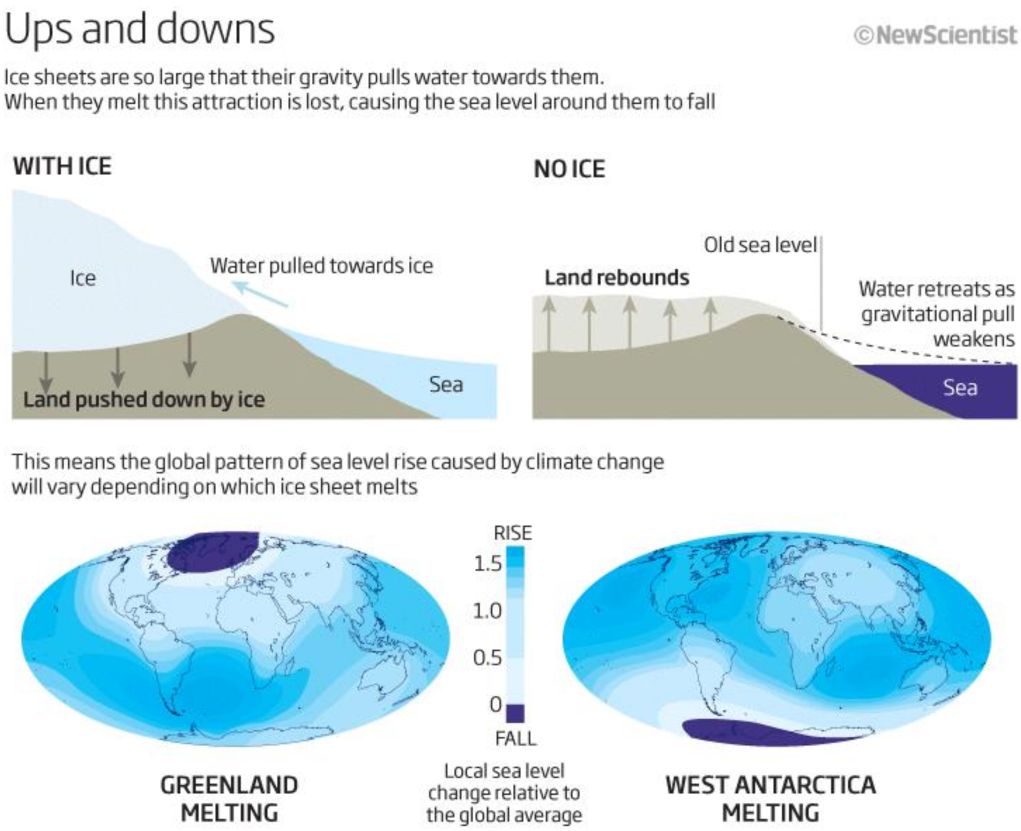
If you think this sounds unlikely then you are in good company, as even oceanographers have struggled to accept the idea. Yet the physics behind it is quite simple and the basic principle was recognised as far back as the 19th century. The first person to do so was Robert Woodward, a physicist who worked for the US Geological Survey at the time when it was becoming clear that much of North America had been covered by ice not that long ago.

Woodward was asked by his colleagues to help explain a puzzling finding: when the ice was present, the shoreline of one lake appeared to have been much higher on one side than the other. He realised that any large mass on Earth's surface, from a continent to an ice sheet, exerts a significant gravitational pull on any water surrounding it, piling the liquid against its flanks. In the case of an ice sheet, these watery foothills will subside if the ice melts. In 1888, Woodward published a paper describing ways to calculate the resulting changes in sea level.

Nearly a century later, in 1976, William Farrell and James Clark factored in the effects of gravity when they tried to work out how sea level changed as the great northern ice sheets melted at the end of the last ice age. The following year, Clark and Craig Lingle applied the same principles to work out what would happen if the fragile West Antarctic ice sheet were to thin or disappear. Sea level around most of the Earth will rise, they found, but in parts of the southern ocean it will fall, producing a distinctive global "fingerprint".

That 1977 finding was not hidden away in some obscure journal – it was in Nature – but remarkably the message still didn't get through. "The idea of sea level fingerprints has a long history of being forgotten," says Mitrovica, who is at Harvard University. Oceanographers continued to talk about average sea level, assuming that a melting ice sheet would deliver a uniform change around the globe. To this day, most maps purporting to show the effects of sea level rise are based on this simplistic assumption.

Yet it has long been at odds with the measurements. The tide gauges monitoring sea level at hundreds of locations around the globe were showing a slow rise in average sea level, but there were large regional variations. "The people looking at tide gauge data saw that sea level was changing from place to place," says Mitrovica, "but they had forgotten about the effect of gravity, so they thought this was a problem." In the 1990s, the TOPEX/Poseidon satellite gave us a detailed global view of the oceans for the first time, and confirmed these puzzling variations in the seascape (see a video showing how the strength of gravity varies around the globe).



At first oceanographers suspected a hangover from the last ice age was to blame. It has been known since the 19th century that the weight of an ice sheet pushes down the Earth's crust. As the crust sinks, deep rock oozes sideways, making surrounding areas bulge upwards. When the ice melts and the weight is lifted, the crust returns to its previous shape. While the gravity effect was largely forgotten, post-glacial rebound remained common knowledge.

The vast ice sheets on North America and Eurasia were so heavy that the land surface below them sank by as much as 500 metres. When the ice began melting around 20,000 years ago, the crust rebounded part of the way very rapidly. "It's like letting go of a stretched elastic band," says Mitrovica. After that, the process continued far more slowly. Some places are still rising today – Hudson Bay lifts by as much as a centimetre per year, for example – while areas that once bulged upwards are still sinking. In these places, sea level will appear to be falling or rising.

The pattern of post-glacial adjustment helps explain some of the regional variations recorded by tide gauges, but it doesn't explain them all. For instance, rebound can't account for the relatively slow sea level rise seen across Europe compared with the global average. Oceanographers were stumped, and climate-change deniers delighted. They cited the stubborn discrepancy as a failure of climate science. "The sceptics forced us to think a bit more carefully," says Mitrovica.

He began to question the even-filling bathtub model in the 1990s. "I thought, well wait a minute, why are we expecting things to be uniform?" Along with his colleagues, Mitrovica ran a series of simulations of ice sheet melting to see how the whole earth and ocean system responds. As well as the two powerful influences of gravity and rapid rebound, the team included some lesser effects, such as changes in Earth's rotation.

Removing an ice sheet is like moving a weight on the rim of a wheel: it alters the planet's balance. If Greenland melts, for example, that will shift our axis of rotation about half a kilometre towards the ex-icesheet. Our equatorial bulge in turn will tilt slightly. This adds extra bumps to the sea level fingerprint, moving the surface up or down by as much as half a metre in places (see diagram).

Mitrovica's team showed in 2001 that by allowing for all these effects, they could explain the geographic variability in tide gauge trends. "That was the 'oh boy!' moment for us," he says. More people began to take notice, although it is only in the past few years that sea-level fingerprints have finally entered oceanography's mainstream.

Outside the field, the notion of shifting seascapes still comes as a surprise, says Mitrovica. "I still give many talks where people are shocked that sea level falls near a melting ice sheet." And his "near" is actually quite far. The long reach of gravity means sea level will fall within about 2000 kilometres of the ice.

If Greenland's ice were to go completely, then the sea around northern Scotland would subside by more than 3 metres. Around Iceland, it would fall by 10 metres. While most coasts around Europe would see levels rise, it would be by far less than the fearsome global average of 7 metres. But all that water has to go somewhere, so more distant parts of the world will have above-average rises. South America will fare particularly badly, with rises of up to 10 metres.

Damoclean icicle

If you live in within a few thousand kilometres of Greenland, and you are of a selfish disposition, this might sound reassuring... but these numbers only apply to its ice sheet. A second Damoclean icicle dangles over our heads at the other end of the world, in the form of the delicate West Antarctic ice sheet. If that melts, it will add between 3 and 6 metres to average sea level, and imprint a very different pattern on the oceans.

Sea level near Antarctica will fall. Around the southernmost tip of South America, the rise will be slight. But most of the world's coasts will see rises greater than the global average. The US east coast will be particularly unlucky, with rises up to 25 per cent more than the average. On top of that, it happens to be one of those spots where the crust is still slowly sinking after the last ice age, going down by 2 to 3 millimetres per year.

So which pattern are we going to see? Observations show that the Greenland ice sheet is currently losing about twice as much mass as Antarctica, which sounds like sort-of good-ish news for Europe. But the key question is what happens next. Recent studies suggest that the complete melting of the Greenland ice sheet is inevitable, bar some geoengineering fix. However, it is generally assumed the ice will take many centuries or even millennia to melt. Nobody knows for sure – studies of past melting events are of limited relevance, not least because the world has never warmed as fast as it is warming now.

The fate of the West Antarctic ice sheet is even harder to predict. Much of it sits on rock several hundreds of metres below sea level, making it especially vulnerable. Warm water melts ice a lot faster than warm air, and if warm currents start eating the ice away from below, the destabilised sheet could disintegrate much faster than the one covering Greenland.

Here Natalya Gomez, a graduate student working with Mitrovica, had a revelation. "After seeing the fingerprint, with its dramatic ring of sea level fall surrounding the ice sheet, we realised that this must have a profound impact on ice sheet stability," she says. If the sea retreats, less of the ice will be exposed to warm currents. Their calculations, published last year, suggest that the local reduction in sea level as the ice melts is a negative feedback that will slow the ice sheet's retreat (Nature Geoscience, vol 3, p 850). "This is the newest and most exciting twist," says Mitrovica.

On the flip side, rising sea level around West Antarctica due to melting in Greenland could have some destabilising effect, and so far Greenland is melting fastest. Both sheets could lose substantial amounts of ice over the next century or two, producing a sea level fingerprint that is a combination of their individual contributions (see New Scientist's interactive ocean map to explore how seas are likely to rise in the coming decades).

This appears to have happened during the last interglacial period, from 130,000 to 114,000 years ago. During this time, average global temperatures were 1 to 2 LC warmer than preindustrial levels – a level of warming we will pass around the middle of the century. Based on clues such as ancient beaches and coral reefs, it had been thought that the average sea level at that time was 4 to 6 metres higher than today – a flood that could have been generated by Greenland alone. But that analysis ignored the regional variations.

In 2009, a team led by Robert Kopp of Princeton University, including Mitrovica, reanalysed the same data in light of all the factors known to affect local sea level. They concluded that the average sea level at this time was probably more than 8 metres higher than today. "That implies we had sizable collapse of both the West Antarctic and Greenland," says Mitrovica.

How long it will take for the same to happen again nobody can say for sure. But we do at least have a much better idea of where sea level will rise most, and where it will fall. If you want a place by the sea without having to worry about rising waters, Greenland is your best bet. Just don't expect the sea to remain by your place.

This article appeared in print under the headline "High and dry"

Rough seas

The sea moves. That will not be news to you. But waves and tides are only the most ephemeral of the sea's dynamic motions. The wind, weather and currents also carve longer-lasting patterns onto the oceans, raising or lowering parts of its surface for days, weeks, years or even millennia.

As low-pressure weather systems move over the ocean they suck up a bump in the sea surface, though these broad domes are rarely more than about 30 centimetres high. Strong winds can pile up storm surges of several metres, which can have devastating effects – as Superstorm Sandy and Hurricane Katrina showed.

A change in the prevailing winds can have a more insidious effect. Around the Solomon Islands in the western tropical Pacific, sea level has been rising by about a centimetre per year – far faster than the global average – since the mid-1990s. At around that time, wind patterns changed. Calculations by Axel Timmermann at the University of Hawaii and Shayne McGregor at the University of New South Wales in Sydney, Australia, show that the wind has been mixing things up, pumping warm surface waters into the deep ocean to build a thicker and thicker layer of warm water. Warmer regions of the ocean are squeezed upwards by the colder, denser water around them.

Ocean currents create an even more durable seascape. A global conveyor belt of currents is driven by the sinking of cold, salty water in the north Atlantic. To counteract the Coriolis force, due to the rotation of the Earth, and allow currents to continue to flow north-east from the Gulf of Mexico towards the sinking zones, the sea level in parts of the North Atlantic is lower than it would otherwise be.

An influx of fresh, low-density meltwater from Greenland could slow or stop the whole conveyor, says Anders Levermann of the Potsdam Institute for Climate Impact Research in Germany. If the water stops, the lowered areas would rise. The latest models suggest this effect is a little weaker than previously feared, but if the overturning circulation shut down altogether, this effect alone would add up to half a metre to sea level rise in the UK and north-eastern US.