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Sea Level Change

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The headlines

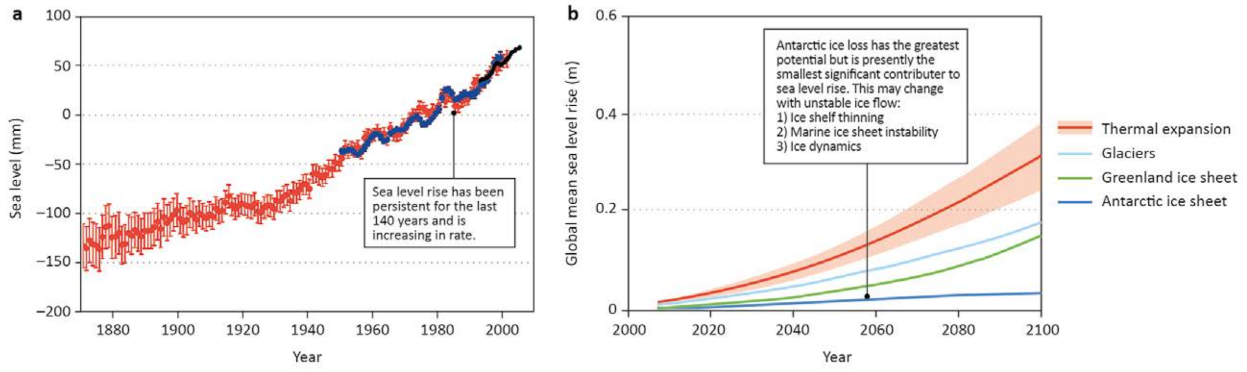
- Melting of ice sheets at the end of the last Ice Age caused 120 m of sea level rise over ~10,000 years
- Sea level has risen by ~20 cm since the mid 19th Century
- 250 million people live in coastal regions less than 5 m above sea level
- Satellite data reveal ice loss in Greenland and Antarctica, which may be irreversible
- Ice sheets are likely to be increasingly important to sea level rise under climate and ocean warming
- The major ice sheets of Greenland and Antarctica together contain enough ice to raise sea level by ~65 m
- Projections of sea level in a 'worst case' greenhouse gas emissions scenario point to at least 80 cm of sea level rise by the end of this century
- Continued greenhouse gas emissions will result in 1-3 metres of sea level rise per degree of warming

Around 250 million people live in coastal regions less than 5 m above sea level. Changes to sea level impact people either directly by flooding or indirectly through the transgression of seawater into cities, farmland and water resources. Knowledge of how and why sea level is changing is, thus, of key importance to society.

How much is sea level changing? Regular recordings of tide gauges in ports across the world have allowed measurements of global sea level spanning at least 150 years. Through time the accuracy of such measurements has improved, and they have been supplemented in the past decades by precise measurements of the world's oceans from satellites. The data show that since the mid nineteenth century sea level has risen by ~20 cm. The rate of sea-level rise has grown over this time to ~3.2 mm each year since the new millennium. In recent research, through better analysis of old data, the rate of twentieth century sea-level rise has been revised down from ~1.75 to ~1.2 mm per year, meaning that the rate of sea-level change today compared with the last century is ~20% greater than thought previously.

Why does sea level change? There are four main processes that lead to sea-level rise. Thermal expansion of water as a consequence of ocean warming; melting of the world's major ice sheets; melting of smaller glaciers; and human-induced changes to the volume of terrestrial water, in particular from the extraction of groundwater and in reservoir development. Thermal expansion accounts for around half of the observed change, with the melting of thousands of small glaciers providing nearly as much. Since the mid eighteenth century, the ice sheets in Antarctica and Greenland have contributed relatively little to sea level.

How much could sea level rise? Under climate warming, the contributions of ocean thermal expansion and glacier melting will continue. The total contribution to sea level possible from melting of the planet's remaining glaciers is ~ 50 cm. For ocean thermal expansion, the contribution is likely to be dependent on the continued warming of sea water. The largest potential contribution to sea level comes from the world's large ice sheets in Greenland, West Antarctica and East Antarctica, which, if melted completely over many centuries would raise the level of the ocean globally by ~7 m, ~5 m and ~53 m, respectively.

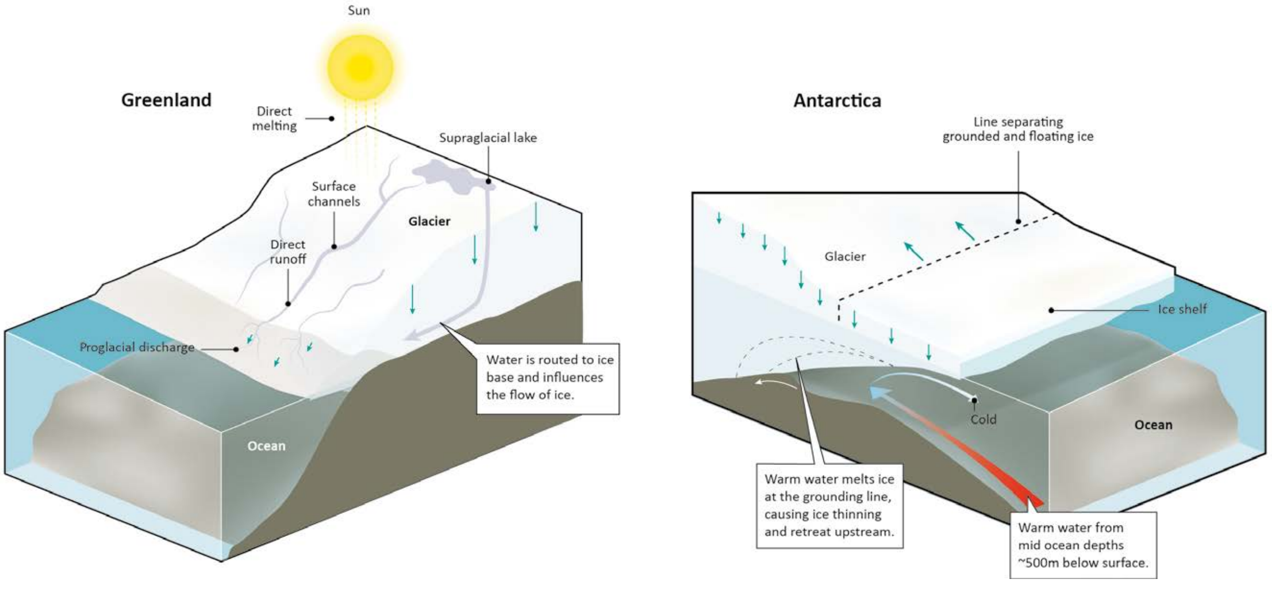


Left hand panel: Global average sea-level change since the mid 19th Century. **Right hand panel:** Components of future of sea-level change under a 'business as usual' climate scenario (IPCC 2013). Note that this IPCC assessment predicts little contribution from the Antarctic Ice Sheet.

How can ice sheets contribute to sea level? The ice sheets of West and East Antarctica and Greenland are distinct, and react to climate warming differently. For Greenland, much of the potential ice loss comes from direct climate warming, leading to surface melting and run-off of water to the ocean (in addition to iceberg release). In West Antarctica, the ice is grounded on a bed over 2 km below present sea level in places, making it known as a 'marine' ice sheet. As the ocean is in direct contact with the ice-sheet edge, the warmth of the ocean water next to the ice is the dominant influence on its rate of melting. Additionally, in a number of locations, West Antarctic ice-sheet retreat would cause the ice edge to migrate across deepening terrain, leading to further enhanced loss – known as 'marine ice-sheet instability'. In East Antarctica, while some regions have 'marine' ice-sheet characteristics, the bulk of the ice rests on land above sea level. While the intense cold of East Antarctica has likely led to its persistence over as much as 14 million years, its size means that even small ice loss changes here can have significant global sea level effects.

In all ice sheets, ice flows from the centre to the edge via ice streams, where the ice is lost to the ocean. This loss is balanced by snow accumulation, so there are only small net changes to sea level. However, alterations to the physical dynamics of ice streams, causing them to speed up or slow down, can lead to rapid changes in the inputs of ice to the ocean and, hence, sudden sea level change.

In West Antarctica, and parts of East Antarctica, the grounded ice is bounded by floating ice shelves, several hundred metres thick. They act as 'buttresses' to the grounded ice, and while their melting would not contribute directly to sea level, as they have already displaced their weight in water, the loss of mechanical support to the grounded ice could result in enhanced flow and, hence, an increase in ice discharge to the ocean.



How does glacier melt work? Left: Diagram showing ice-loss in Greenland through direct melting of ice and run-off (either at the surface or subglacially). **Right:** Diagram showing ice-loss in Antarctica, through ocean-driven melting of ice shelves and grounding line retreat.

The last Ice Age

During the peak of the last Ice Age (~20,000 years ago), sea level was ~120 m lower than today. As a consequence of global warming, albeit naturally, the rate of sea-level rise averaged ~1.2 cm per year for 10,000 years until it levelled off at roughly today's position ~10,000 years ago. Within this change several episodes of extra rapid sea level rise have been recorded, for example at ~ 14,000 years ago when the rate of sea-level rise jumped to ~3 cm per year, as consequence of either a sudden and time-limited ice-sheet reaction to warming or ice-sheet dynamic change.

Ice Age Earth: Global ice cover during the peak of the last Ice Age ~20,000 years ago. Note the substantial ice sheet cover across North America and Northwest Europe, and sea-ice expansion around northern seas and oceans.

Has this happened previously? Sea level has changed naturally over glacial-interglacial cycles, mostly as a consequence of the growth and decay of large ice sheets paced by changes in incoming solar radiation as a consequence of well-understood periodic variations in the Earth's orbit around the Sun (as evidenced in ancient records of climate change from deep-ocean sediments and ice cores). The last time Earth experienced a climate similar to today was 120,000 years ago, in between ice-age episodes. Sea level then was at least ~6 m higher than today, almost certainly because parts of the Greenland and West Antarctic Ice Sheets were smaller than they are now.

Evidence from the past is startling, as it demonstrates that substantial sea-level change is possible under climate warming, and that the rate of change observed today has been exceeded on occasions by an order of magnitude.

How is the ice changing today? Since the early 1990s a number of satellites have been able to measure the elevation of the ocean, and the surfaces of ice sheets. They reveal that the world's ice sheets are losing mass in different ways. For Greenland, the southern half of the ice sheet is experiencing ice loss through surface melting as a consequence of today's climate warming. In East Antarctica, a few regions at the ice edge are experiencing ocean-induced ice loss, but not at significant levels. It is in West Antarctica, and in particular its Amundsen Sea region, where the most substantial and concerning changes have been measured. Here, in the last 20 years, ocean warmth has caused the edges of Thwaites and Pine Island to retreat by 15 and 30 km, respectively. This has led some to consider that marine ice-sheet instability has already begun in this sector of West Antarctica, which could lead to irreversible future sea-level rise on the order of 1.5 m.

Satellite data have also allowed us to measure the sudden disintegration of ice shelves across the Antarctic Peninsula. Several of these, most notably the Larsen B Ice Shelf, have collapsed catastrophically over the past 20 years with immediate knock-on impacts of increasing the flow of grounded ice upstream.

Is human-driven climate warming responsible for the ice-sheet changes? The changes observed in Greenland are almost certainly the result of climate warming, driving increased air temperatures leading to surface melting of the snow and ice.

Thermal expansion of the ocean, and glacier melting, will similarly be due to anthropogenic warming. The changes observed in Antarctica are less obviously linked to human-induced changes, however. The ocean water responsible for Antarctic ice loss is likely to have acquired its warmth several hundred years ago. Hence, modern ocean warming is likely unconnected with these changes. However, the transfer of warmth to the ice is the result of ocean currents, which may have experienced recent change due to modification in atmospheric conditions, such as wind direction. A recent modelling investigation predicts ocean current changes to a particularly vulnerable region of West Antarctica later this century as a consequence of human-induced climate change, which would force West Antarctic change within a century or two.

The rate of ice shelf loss in the Antarctic Peninsula seems well linked to modern climate change, as this region has experienced ‘amplified’ warming. If this warming continues, ice shelves further south may become vulnerable. A major concern is that the loss of the Ross and Filchner-Ronne ice shelves, the largest in Antarctica, would mean the bulk of the West Antarctic Ice Sheet would be exposed to ocean-induced melting and, hence, large-scale marine ice-sheet instability.

How will sea level change in the future? Given the observed trends in sea level, and in global warming, it is virtually certain that sea level will continue to rise over the coming decades due to increased loss of mass from glaciers and ice sheets, and thermal expansion of ocean water.

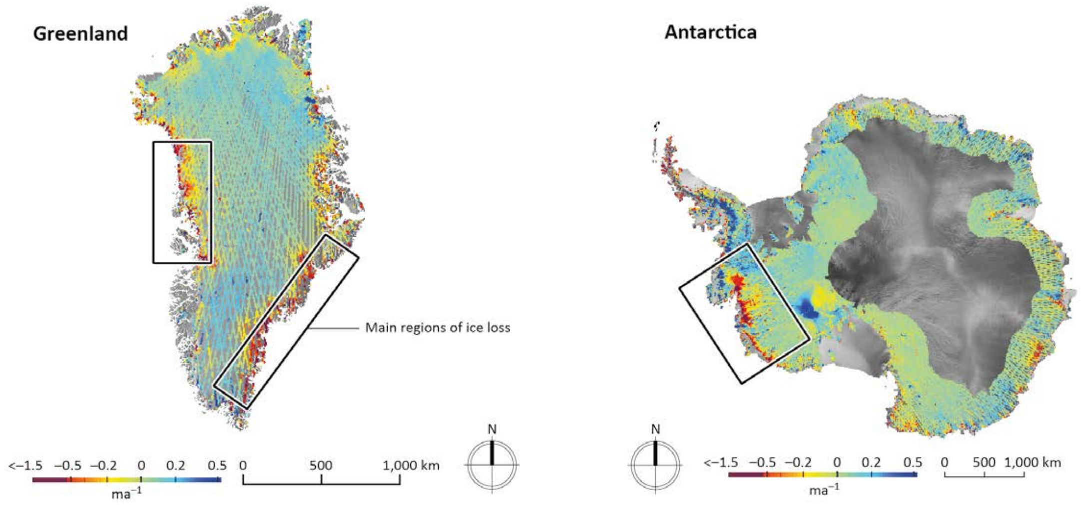
The fourth assessment report of the IPCC in 2007 was uncertain about the contribution of ice sheets to future sea level change. To remedy this, a recent EU-funded project, named Ice2sea, quantified the cryosphere’s ‘likely’ contribution to sea level under a range of atmospheric carbon emission scenarios. Under a ‘business as usual’ emissions scenario, ice sheets are likely to contribute between 3.5 and 36.8 cm by 2100. However, as unstable behaviour in ice sheets is difficult to predict and model, Ice2sea also indicated, via an ‘expert elicitation’ exercise, that there was a less than 1 in 20 risk of ice sheets contributing up to 84 cm to sea level by 2100.

These values must be added to other components of sea level change, to produce an overall likely increase in sea level. The 5th assessment report of the IPCC in 2013 did this and concluded that, under climate scenario RCP8.5 (emissions continuing as now throughout the next century), sea level will likely increase by between ~0.5 and ~1 m by 2100.

The rate of change of sea level rise is also likely to increase, with the IPCC concluding that the RP8.5 scenario will lead to an increase in the rate of change to between ~0.7 and ~1.6 cm per year by 2100; values reminiscent of sea-level rise during the end of the last Ice Age.

How will sea level rise affect the UK? The effect of ice sheet melting on sea level is non-uniform across the world. This is because of the significant mass of large ice sheets, which act as gravitational attractions to water, raising the level of the ocean near to the ice as a consequence. As the ice melts, this attraction reduces, so lowering sea level in regions close to the ice. Away from the ice (such as the other hemisphere), the gravitational attraction is negligible. For this reason, the UK will experience hardly any sea-level effect from melting of the Greenland Ice Sheet, but will experience the maximum possible effect of changes in Antarctica.

The UK is used to dealing with rising sea level on rare occasions and over short timescales, due to storm surges during spring tides. If the IPCC predictions are correct, we must consider the increase in sea level predicted on top of natural tidal surges. This will make disruptive storm-surge events occur more often in the coming decades, and will increase the destructiveness of the most intense surges compared with those witnessed to date.



Where does ice-sheet loss occur? Left: ICESat surface elevation change in Greenland, revealing the zones of major ice sheet loss. **Right:** ICESat surface elevation change in Antarctica, revealing zones of major ice sheet loss.

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About the author

Martin Siegert is Professor of Geosciences and Co-Director of the Grantham Institute, Imperial College London. He was formerly director of the Bristol Glaciology Centre, University of Bristol, and Head of the School of GeoSciences at the University of Edinburgh. He was awarded his PhD in the numerical modelling of large ice sheets from Cambridge University, at the Scott Polar Research Institute.

Siegert's research interests are in the field of glaciology. He uses geophysical techniques to quantify the flow and form of ice sheets both now and in the past. Using airborne radar he has identified and located ~400 subglacial lakes, has discovered ancient preglacial surfaces hidden beneath the existing ice and has demonstrated how sub-ice water is generated and interacts with the flow of ice above. He leads the UK NERC Lake Ellsworth Consortium, which aims to directly measure and explore an ancient subglacial lake in West Antarctica, to search for life in its water and comprehend records of climate held in sediments. In 2007 he was elected a Fellow of the Royal Society of Edinburgh. He was awarded the 2013 Martha T Muse Prize in Antarctic Science and Policy.

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