3. Polar ice sheets: contribution to sea-level rise

Global sea level has fluctuated considerably over millennia by several 10's of metres due to the advance and retreat of polar ice sheets and glaciers. During the Last Glacial Maximum (Ice Age) 20,000 years ago, glaciers advanced covering about 8% of the Earth's land area and causing ocean levels to drop 120 m below modern sea level[1]. Current stores of ice in glaciers and polar ice sheets (the 'cryosphere') are the equivalent of 65 m of sea-level rise[1] – however loss of this magnitude is unlikely to happen for millennia (given the Antarctic ice cap has survived much warmer eras). Nonetheless, these large fluctuations indicate the serious potential for polar ice sheets to contribute a substantial contribution to future sea-level rise if global emissions are not curtailed.

Polar ice sheets (mainly Greenland and Antarctica) and mountain glaciers contribute to sea-level rise by adding water mass to the oceans as they melt or break up. The contribution of additional water mass from the cryosphere is accelerating (see Box 1) and over century time scales will be a larger contributor to sea-level rise than any other source. Presently, glaciers and ice sheets contribute to around 43% of recent sea-level rise, but this will rise to 57–61% contribution by 2100 depending on emissions and physical processes (Primer #1).

Box 1: IPCC AR6 summary statements on observations of glacier and ice environments

- Both the Greenland and Antarctic Ice Sheets have lost mass since satellite observations started in 1992. For the period 1992-2020, Greenland has lost on average 168 giga-tonnes per year of ice mass to the ocean and Antarctica, an average of 92 giga-tonnes annually. [This recent yearly average, combining both ice sheets, is the equivalent of 2.5 m depth of ice per year if it was stacked over the entire North Island.]
- Mountain and polar glaciers will continue melting for decades or centuries (*very high confidence*).
- Continued ice loss over this century is *virtually certain* for the Greenland Ice Sheet and *likely* for the Antarctic Ice Sheet. There is *high confidence* that the total amount of ice loss from the Greenland Ice Sheet will increase with cumulative emissions. There is *limited evidence* for low-likelihood, high-impact outcomes under high emissions scenarios that would strongly increase ice loss from the Antarctic Ice Sheet for centuries. This would result from ice-sheet instability processes (some not well understood) and in some cases involving tipping points for irreversible change to continued melting.

Source: IPCC 2021 (Working Group I): Summary for Policymakers' and Chapter 9. https://www.ipcc.ch/

Because sea ice and coastal polar ice shelves already float in the ocean, they don't contribute to sea-level rise when they break off and melt. However, collapse of ice shelves along the coast of Antarctica contributes indirectly to sea-level rise, as it unplugs glaciers flowing off the mainland. These glaciers thin out and accelerate their ice flow into the ocean, which directly adds to the rising sea level, besides meltwater runoff.

Several processes cause ice sheets to lose mass (Figure 1). The key processes leading to ice loss are ice shelf-fracturing and melting at the surface, while below at the grounding line, warming ocean water melts and retreats the edges of the ice sheet. If the seabed slopes downwards as the grounding line retreats, this can readily trigger a runaway unstable situation that further accelerates ice loss. This is most relevant to West Antarctica, where much of the ice sheet sits on bedrock that is well below current sea level.[2]

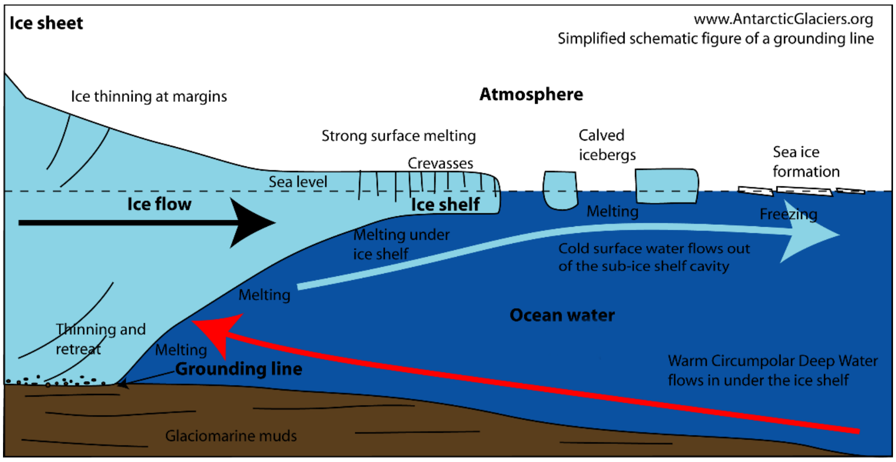

Figure 1:

Schematic of a polar glacier extending into an ice shelf, showing the grounding line (where the glacier begins to float) and how an ice shelf can be thinning and fracturing from the surface and from below due to warmer ocean water.

Source: *www.AntarcticGlaciers.org* and *https://joidesresolution.org/the-crucial-role-of-ice-shelves/*

How projections are made for the ice-sheet contribution to sea-level rise

Scientific understanding of how glaciers and ice sheets are changing has improved rapidly over recent decades, due to considerable improvements in both the accuracy and density of observations, and in the complexity of the computer models used to simulate ice flow. By using models that incorporate more of the known physical processes that affect the cryosphere, and by using observational measurements to train these models, simulations are increasingly able to realistically capture present-day ice flow behaviour. This then allows for more trustworthy projections of future contributions to sea level, Although there is still considerable uncertainty surrounding our likely future emissions, ensembles of simulations can be run that span the most likely spread of climate scenarios and the range of possible ice sheet responses. However, there are also concerns that processes that are poorly understood may play out in a warmer climate. These 'low likelihood' scenarios could potentially accelerate ice loss and trigger much faster sea-level rise. One of the best ways to assess the possible consequences of such unknown processes is to look at the geological evidence from times in the past when climate was warmer than present, to see if information can be found that reveals how fast ice sheets have retreated before.

Conclusions

In summary, the evidence is unequivocal that ice is melting around the world, and that glaciers and ice sheets are retreating faster than they have for thousands of years. Even under our current climate we are committed to ongoing future melting and the consequent effect on global sea level. For every degree of additional warming both the rate and amount of sea level rise will increase. These changes will persist for millennia, and on human time-scales may be irreversible.

Monitoring ice loss from polar ice sheets

Until the advent of satellites, measurements of ice sheet loss were limited to local study sites. From 1992 onwards, satellites with altimetry sensors (which send and receive radio pulses or laser beams) were able to traverse much larger areas of the Greenland and Antarctic ice sheets. Ice sheets grow higher through the accumulation of snowfall when annual snowfall exceeds annual snowmelt. But when the melt or thinning processes are more than the annual snowfall, the elevation drops. A second way is to calculate an ice-mass balance, requiring a input (snowfall), elevation change (from satellites) and the outflow to the ocean (knowing the speed and cross-section of the ice flow) to give the net change. By 2002, scientists were able to use these advances to show that both large ice sheets were losing mass.

Further advances were made in 2003, when the GRACE satellite was launched by NASA. This platform measured changes in the Earth's gravity field over the ice sheets, which created a third way of indirectly measuring changes in ice sheet stores. These monitoring techniques have been immensely helpful in quantifying the extent of ice loss, how it is accelerating[3] and provided real data to verify climate and ice-sheet models.

[1] https://www.usgs.gov/faqs/how-does-present-glacier-extent-and-sea-level-compare-extent-glaciers-and-global-sea-level
[2] Fretwell et al. (2013). Bedmap2. https://doi.org/10.5194/tc-7-375-2013
[3] https://www.esa.int/Applications/Observing_the_Earth/Space_for_our_climate/Clearest_evidence_yet_of_polar_ice_losses