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## Ocean forcing of glacier retreat in the western Antarctic Peninsula

### Authors:

A. J. Cook<sup>1,2\*</sup>, P. R. Holland<sup>3</sup>, M. P. Meredith<sup>3</sup>, T. Murray<sup>1</sup>, A. Luckman<sup>1</sup>, D. G. Vaughan<sup>3</sup>

### Affiliations:

<sup>1</sup> Department of Geography, Swansea University, Swansea, UK.

<sup>2</sup> Department of Geography, Durham University, Durham, UK.

<sup>3</sup> British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK.

\*Correspondence to: alison.cook@durham.ac.uk

### Abstract:

In recent decades, hundreds of glaciers draining the Antarctic Peninsula (63-70 °S) have undergone systematic and progressive change. These changes are widely attributed to rapid increases in regional surface air temperature, but it is now clear that this cannot be the sole driver. Here we identify a strong correspondence between mid-depth ocean temperatures and glacier-front changes along the ~1000-km western coastline. In the south, glaciers that terminate in warm Circumpolar Deep Water have undergone considerable retreat, while those in the far north-west, which terminate in cooler waters, have not. Furthermore, a mid-ocean warming since the 1990s in the south is coincident with widespread acceleration of glacier retreat. We conclude that changes in ocean-induced melting are the primary cause of retreat for glaciers in this region.

### Main Text:

The Antarctic Peninsula (AP) glaciers north of 70 °S have the potential to raise sea level by  $69 \pm 5$  mm (1) so any imbalance in their mass budget is of global importance. The region has undergone rapid warming in the latter half of the 20<sup>th</sup> Century (2), and it is widely accepted that this has had a substantial impact on the ice sheet (3-6). The established theory that retreat of floating ice shelves is linked to a southerly migration of an atmospheric thermal limit (7), might also be considered likely to apply to retreat of marine-terminating glacier fronts. Indeed, the most significant glacier area loss over the past few decades has occurred in the north-east (8), which is north of the thermal limit and where the atmospheric temperature rise has been greatest.

Glaciers flowing westwards from the AP plateau have, however, shown notable differences in frontal change over the same period. Overall ice loss has been greater in the

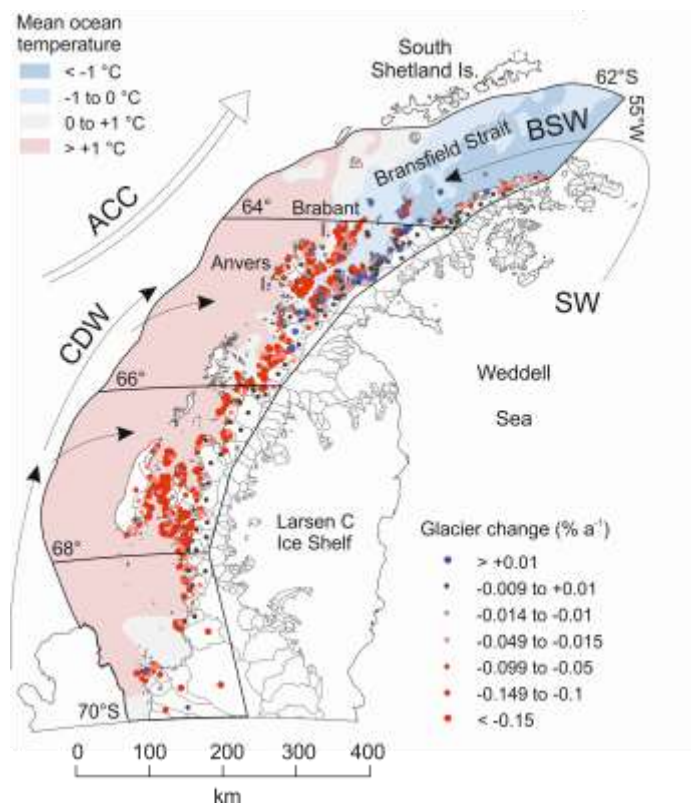
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south than the north, and glaciers in the north-west have remained stable (8). A previous study suggested that atmospheric warming may not be responsible for glacier change in this region because the migration from advance to retreat implied a warming more rapid than that observed (9). Indeed, spatial and temporal patterns of atmospheric forcings including surface temperatures (10), melt duration (4) and precipitation (11), exhibit no clear relationship with the distinct north-south gradient of glacier-front changes along the west coast (8).

In the south-western Bellingshausen Sea, rapid thinning of the ice shelves and their tributary glaciers has occurred during the past decade (12, 13), and it has been proposed that this is caused by changes in upper-ocean heat content (14, 15). The much larger ice loss from the West Antarctic Ice Sheet has also been linked to changes in heat content in the adjacent Amundsen Sea (16, 17), which is similarly dominated by Circumpolar Deep Water (CDW) in its deeper layers. There, basal melting causes ice-shelf thinning, grounding-line retreat, and a loss of buttressing to the grounded ice inland. Variations in tidewater glacier termini are more complex, but several recent studies of Arctic glaciers have concluded that calving rates are strongly dependent on ocean temperatures (e.g. 18). Until now, the role of the ocean (as opposed to the atmosphere) as the dominant influence of glacier frontal retreat on the western AP has not been considered.

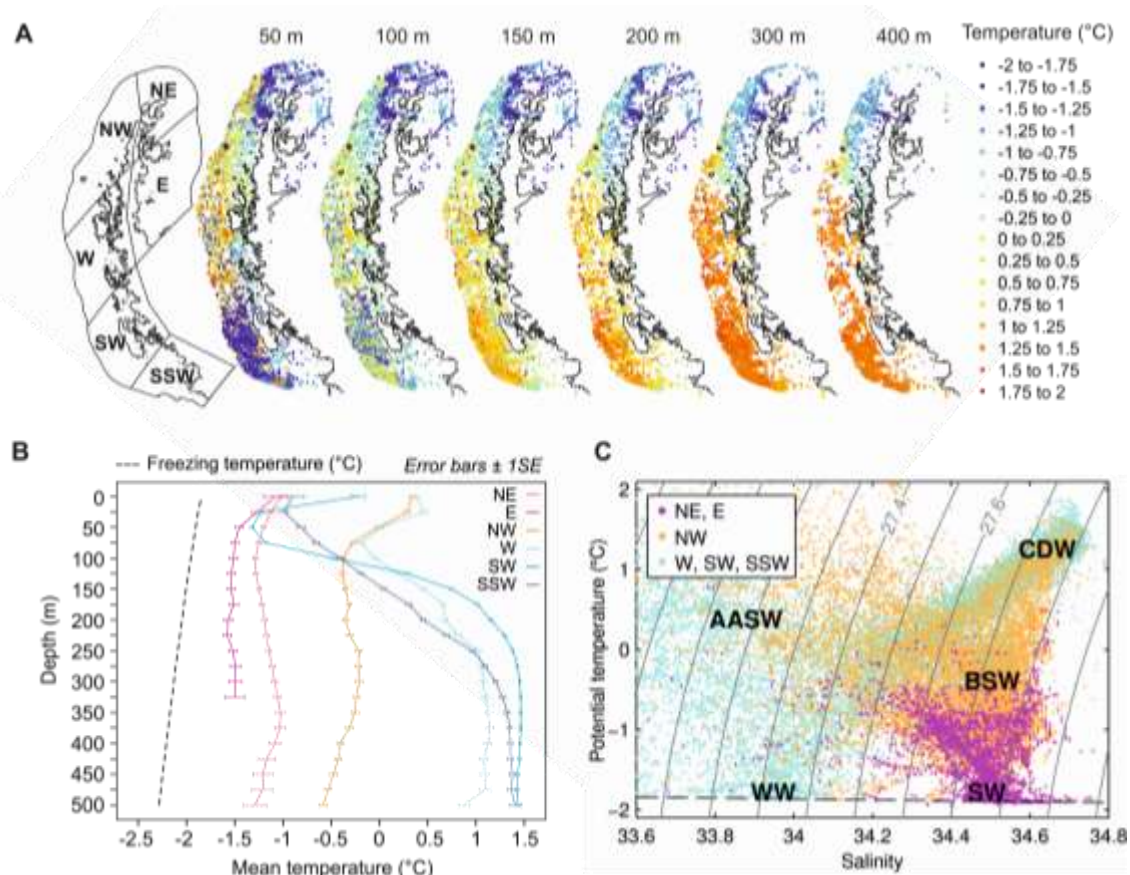
Although the oceans around Antarctica are notoriously data-sparse, the World Ocean Database 2013 (19) contains a sufficiently high spatial density of ocean temperature and salinity measurements to the west of the AP to enable regional mean temperature estimations (1945-2009) (20). When considered alongside observed changes in the glacier fronts (Fig. 1) a strong spatial correlation between the distribution of retreating glaciers and the pattern of mean ocean temperature over this period is revealed. Nearly all the glaciers south of Brabant and Anvers islands (~65 °S), which discharge into warm ocean regions dominated by CDW, have suffered retreat. In contrast, the more northerly glaciers, which discharge into the cooler Bransfield Strait Water (BSW), experienced only small frontal changes indicative of relative stability over the 65 years for which observations are available. Furthermore, a southwards increase in ice loss per glacier revealed in an earlier study (8) corresponds to a distinct and coherent spatial distribution in ocean temperatures (Fig. 2A). Ocean temperatures in this region are highly variable in the upper 100 m, but a pronounced north-south gradient becomes progressively more apparent at greater depth.

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**Fig. 1:** Mean ocean temperatures and overall glacier area changes 1945-2009. Mean in-situ ocean temperature at 150 m depth (shaded) and glacier change (points). For each glacier along the west coast the point shows overall change between its earliest and latest recorded ice-front position, relative to basin size ( $\% a^{-1}$ ). A similar spatial pattern is found for changes in absolute area loss per glacier. The point symbols are layered in the same order as in the legend (i.e. blue above red). Ocean circulation and water masses are also shown schematically: Circumpolar Deep Water (CDW), Shelf Water (SW), Bransfield Strait Water (BSW), and Antarctic Circumpolar Current (ACC).

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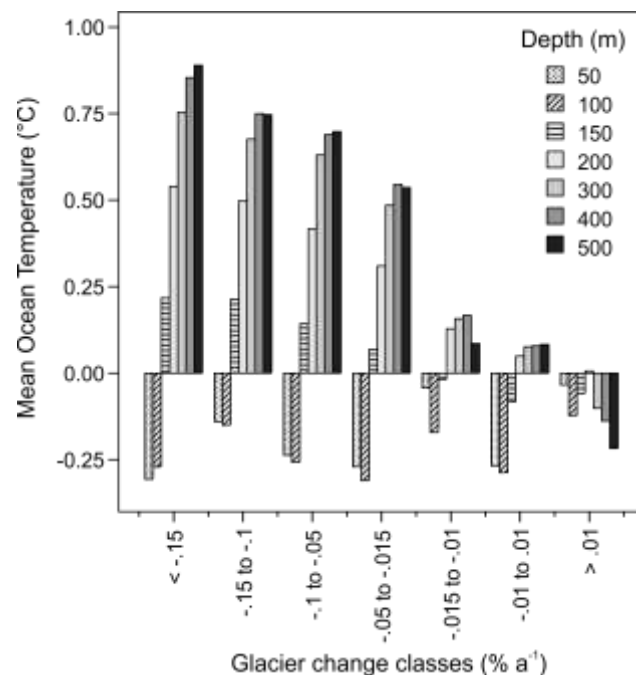


**Fig. 2:** Ocean conditions surrounding the Antarctic Peninsula. **(A)** In-situ temperature of the ocean surrounding the AP at specific depths. The six regions are defined by east/west and by two-degree latitudinal bands, up to 100 km off the AP coast. **(B)** Mean in-situ temperature profile in each region. The dashed line is the in-situ freezing temperature. **(C)** Potential temperature - salinity diagram showing the different water masses in different regions, namely Shelf Water (SW), Bransfield Strait Water (BSW), Circumpolar Deep Water (CDW), Winter Water (WW), and Antarctic Surface Water (AASW). Grey lines are contours of surface density anomaly, and the dashed line is the freezing temperature.

Partitioning the ocean adjacent to the AP into six regions of approximately equal area reveals three distinct oceanographic regimes (21, 22) (Figs 2B and 2C). To the south and west, warm and saline CDW is prevalent across the Bellingshausen Sea shelf. This CDW is overlain by colder and fresher Winter Water and Antarctic Surface Water formed by the interaction of CDW with the cryosphere and atmosphere. To the north-east, the Weddell Sea shelf contains cold and saline Shelf Water, which is heavily influenced by heat loss to the atmosphere and sea ice production in the Weddell Sea. In Bransfield Strait, north-west of the AP, the BSW is a mixture of Shelf Water and variants of CDW, again modified by air-sea-ice interaction. Crucially, these three water masses present very different thermal forcing to the glaciers abutting the ocean: the Shelf Water, BSW, and CDW average approximately 1, 2, and 4 °C above the seawater freezing temperature respectively (Fig

2C). Glacier melting is expected to increase linearly or above-linearly with temperature above freezing, depending upon the geometry of the ice face and presence of subglacial meltwater discharge (23, 24).

The relationship between the ocean temperatures and glacier front change is also quantitatively robust (Fig. 3): glaciers that have the warmest ocean temperatures near their fronts have retreated most significantly, and glaciers that are adjacent to the coolest water have remained stable or advanced. The relationship is strongly depth-dependent: temperatures at and below 150 m depth display similar correlations, while at shallower depths there is no systematic relationship. The skewed nature of the glacier change rates (attributed to the wide range of glacier basin areas and characteristics) precludes linear regression, but when tested by rank order, strong correlations become apparent (Table S1). Spearman's Rank correlation between relative change rates (in  $\% a^{-1}$ ) and mean temperatures becomes stronger with depth: there is no correlation at 50 and 100 m, but deeper than this, the correlations are statistically significant ( $P < 0.01$ ).



**Fig. 3:** Mean overall glacier changes (binned) and mean in-situ ocean temperature (within 5 km of glacier fronts) at specific depths. Negative glacier change values signify retreat: the x-axis reads from largest retreat rates on the left towards small changes and advances on the right.

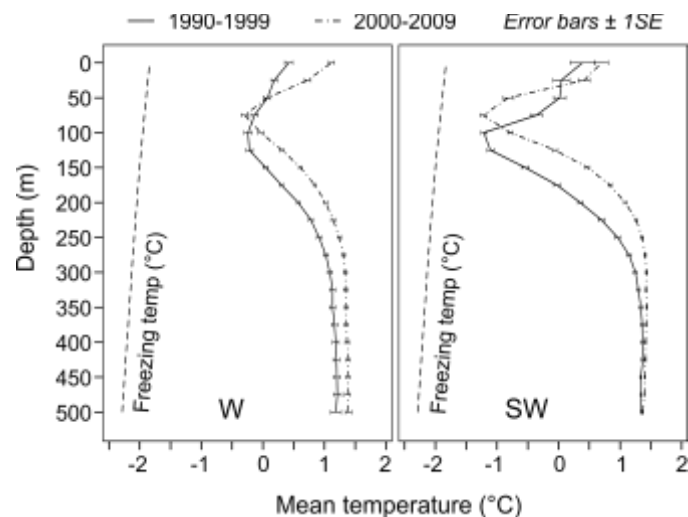
A relationship between ice-front history and deep ocean temperature is consistent with the expected dynamics of ocean melting of glacier ice, in locations where the seabed is sufficiently deep. Several studies have shown that release of fresh, buoyant meltwater causes an upwelling at the ice face that draws in water at depth, and drives a flow away from the glacier at the surface or pycnocline (25-27). Where present, this circulation

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preferentially delivers source waters for melting at depth, with melting comparatively insensitive to the properties of the shallower waters. The available bathymetric data for the western AP region support a connection between the deeper shelf waters and the glacier fronts (Fig. S1).

We hypothesize that the spatial relationship between ocean properties and glacier change in the western AP is a consequence of the differing thermal characteristics of the two oceanographic regimes. The regimes have different temporal variabilities, with CDW variations originating in the transport and mixing of water from the Antarctic Circumpolar Current, and BSW variations originating in atmosphere-ocean interaction and sea ice formation over the Weddell Sea shelf (28). Ocean heat content in the Bellingshausen Sea is known to have increased, attributed to an increase in CDW upwelling onto the shelf, a decrease in heat loss to the atmosphere, and a slow warming of the CDW offshore of the shelf (29, 30). In common with changes on the Amundsen Sea shelf (17), the primary manifestation of the changing heat content is a change in the thickness of the deep CDW layer through a shoaling of the pycnocline. The BSW further north, however, originates in a different climatic regime to the CDW, where ocean temperatures are constrained near the surface freezing point by sea-ice processes, thus removing the potential impact of any temperature variability.

Although there are too few repeated ocean measurements prior to the 1990s to establish the significance of oceanic changes over the full period of glaciological data, there are sufficient observations of the northern Bellingshausen Sea to examine changes there since 1990. These observations reveal that the ocean was warmer on average in the 2000s than the 1990s, particularly at depths between 100 and 300 m in the SW region (Fig. 4). During the late 1990s, a universal acceleration in glacier retreat occurred, apparent in all coastal regions except in the north-west (8) (Fig. S2). The available oceanographic observations are therefore consistent with our hypothesis of ocean-driven glacier retreat.



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**Fig. 4:** Mean in-situ temperatures during the 1990s (solid line) and 2000s (dot-dash line) for repeated measurements in the W and SW regions. The measurements were taken during cruises that occurred in the austral summer, with spatial coverage spanning the two regions.

We conclude that ocean temperatures below 100 m depth have been the predominant control on multi-decadal glacier front behaviour in the western AP. Glaciers abutting the warm, and warming, CDW regions in the Bellingshausen Sea have retreated, while those discharging into cooler BSW in Bransfield Strait have not. The wide-scale regional ocean temperature pattern has existed since the earliest records, and the ocean heat content in regions dominated by CDW has increased since at least as long ago as the 1990s. Warming has primarily occurred at mid-depths (100-300 m) in these regions. Most importantly, ocean warming has occurred concurrently with a widespread acceleration in glacier retreat.

Ice shelves further south in the Bellingshausen Sea are already recognized as being susceptible to ocean forcing (13, 14, 31), but this study shows that relatively warm coastal seas are also driving frontal retreat in 596 (90%) of the 674 marine-terminating glaciers further north. Indeed, the climatic setting and marine-terminating nature of these AP glaciers mean they share greater similarity to other “near-polar” environments where similar marine-terminating glaciers dominate (e.g. Greenland, Alaska, Patagonia, Svalbard, and some sub-Antarctic islands) than to the rest of Antarctica. Furthermore, our results emphasize the likely sensitivity of all such systems to changes in deep coastal waters, and caution against assuming the dominance of atmospheric forcing, even where that warming is strong, as in the case of the AP. Our observations demonstrate clearly that simulations of glacier change over the last half-century that are driven solely by atmospheric climate (e.g. 32) would fail to capture the most salient processes driving ice-loss in the Antarctic Peninsula. It follows that predictive models employed to project future ice-loss from glacial systems where marine-terminating glaciers abound, will require coupling to oceanic, as well as atmospheric forcing.

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## Supplementary Materials

[www.sciencemag.org](http://www.sciencemag.org)

Materials and Methods

Figs. S1, S2

Table S1

Database S1

References (33)

## Acknowledgements



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