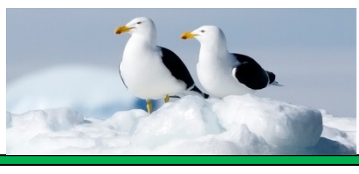
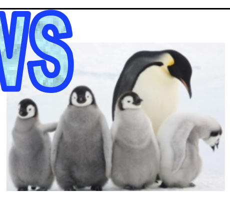
ANTARCTIC GLACIER NEWS





News date: 14th July 2016 compiled by Dr. Alvarinho J. Luis

Ocean warming primary cause of Antarctic Peninsula glacier retreat

A new study has found for the first time that ocean warming is the primary cause of retreat of glaciers on the western Antarctic Peninsula. The Peninsula is one of the largest current contributors to sea-level rise and this new finding will enable researchers to make better predictions of ice loss from this region.

A new study has found for the first time that ocean warming is the primary cause of retreat of glaciers on the western Antarctic Peninsula. The Peninsula is one of the largest current contributors to sea-level rise and this new finding will enable researchers to make better predictions of ice loss from this region.

The research lead by scientists at Swansea University and British Antarctic Survey, is published in the journal *Science,* July 15 issue. The study reports that glaciers flowing to the coast on the western side of the Peninsula show a distinct spatial correlation with ocean temperature patterns, with those in the south retreating rapidly but those in the north showing little change. Some 90% of the 674 glaciers in this region have retreated since records began in the 1940s.

Dr Alison Cook, who led the work at Swansea University, Scientists pointed out that ocean warming is affecting large glaciers elsewhere on the continent, and argued that atmospheric temperatures were the primary cause of all glacier changes on the Peninsula.

The numerous glaciers on the Antarctic Peninsula give a key insight as to how environmental factors control ice behavior on a wide scale. Almost all glaciers on the western side end in the sea. They were able to monitor changes in their ice fronts using images as far back as the 1940s. Glaciers here are extremely diverse and yet the changes in their frontal positions showed a strong regional pattern.

They were keen to understand what was causing the differences, in particular why the glaciers in the north-west showed less retreat than those further South and why there was acceleration in retreat since the 1990s. **The ocean temperature records have revealed the crucial link.**

The team studied ocean temperature measurements around the Peninsula stretching back several decades, alongside photography and satellite data of the 674 glaciers.

The north-south gradient of increasing glacier retreat was found to show a strong pattern with ocean temperatures, whereby water is cold in the north-west, and becomes progressively warmer at depths below 100 m further south. Importantly, the warm water at mid-depths in the southerly region has been warming since as long ago as the 1990s, at the same time as the widespread acceleration in glacier retreat.

Co-author Prof. Mike Meredith at British Antarctic Survey pointed out that these new findings demonstrate for the first time that the ocean plays a major role in controlling the stability of glaciers on the western Antarctic Peninsula. Where mid-depth waters from the deep ocean intrude onto the continental shelf and spread towards the coast, they bring heat that causes the glaciers to break up and melt. These waters have become warmer and moved to shallower depths in recent decades, causing glacier retreat to accelerate.

Co-author Prof. Tavi Murray, who leads the Glaciology Research Group at Swansea University, opined that the glaciers on the Antarctic Peninsula are changing rapidly -- almost all of the Peninsula's glaciers have retreated since the 1940s. We have known the region is a climate warming hotspot for a while, but we couldn't explain what was causing the pattern of glacier change.

This new study shows that a warmer ocean is the key to understanding the behavior of glaciers on the Antarctic Peninsula. Currently the Peninsula makes one of the largest contributions to sea-level rise, which means understanding this link will improve predications of sea-level rise.

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30. Previous studies leveraging high-throughput experimentation at Merck validated 5% yield as a good screening hit and 20% yield as a robust hit.
31. P. S. Kutchukian et al., Chem. Sci. (Camb.) 7, 2604–2613 (2016).
32. $NiCl_2$ has been reported as a heterogeneous catalyst for the N-arylation of aryl iodides under microwave conditions in the absence of an exogenous ligand (33).
33. A. K. Gupta, G. T. Rao, K. N. Singh, Tetrahedron Lett. 53, 2218–2221 (2012).
34. Although we favor the mechanism outlined in Fig. 2, we cannot rule out the possibility of energy transfer or direct excitation of Ni(II) in the presence of visible light.

ACKNOWLEDGMENTS

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/353/6296/279/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S12
References (35–48)
NMR Spectra

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GLACIERS

Ocean forcing of glacier retreat in the western Antarctic Peninsula

A. J. Cook,[1,2]* P. R. Holland,[3] M. P. Meredith,[3] T. Murray,[1] A. Luckman,[1] D. G. Vaughan[3]

In recent decades, hundreds of glaciers draining the Antarctic Peninsula (63° to 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-kilometer western coastline. In the south, glaciers that terminate in warm Circumpolar Deep Water have undergone considerable retreat, whereas those in the far northwest, 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.

The Antarctic Peninsula (AP) glaciers north of 70°S have the potential to raise sea level by 69 ± 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 20th 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 northeast (8), which is north of the thermal limit and where the atmospheric temperature rise has been greatest.

Glaciers flowing westward from the AP plateau have, however, shown notable differences in frontal change over the same period. Overall ice loss has been greater in the south than the north, and glaciers in the northwest 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 southwestern 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 driver 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 to 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 southward 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.

Partitioning the ocean adjacent to the AP into six regions of approximately equal area reveals three distinct oceanographic regimes (21, 22) (Fig. 2, B and C). 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 (WW) and Antarctic Surface Water (AASW) formed by the interaction of CDW with the cryosphere and atmosphere. To the northeast, 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 the Bransfield Strait, northwest 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 the 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,

[1]Department of Geography, Swansea University, Swansea, UK. [2]Department of Geography, Durham University, Durham, UK. [3]British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK.
*Corresponding author. Email: alison.cook@durham.ac.uk

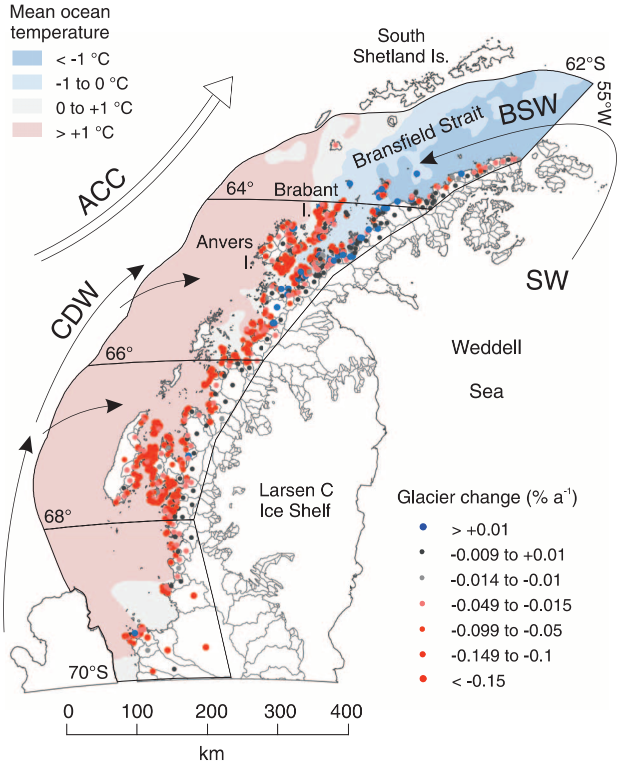

Fig. 1. Mean ocean temperatures and overall glacier area changes, 1945 to 2009. Mean in situ ocean temperature at 150-m depth (shaded) and glacier change (points). For each of the 674 glaciers along the west coast, the point shows overall change between its earliest and latest recorded ice-front position, 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: CDW, Shelf Water (SW), BSW, and ACC.

whereas 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 ($P < 0.01$).

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 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 (ACC) and BSW variations originating in atmosphere-ocean interaction

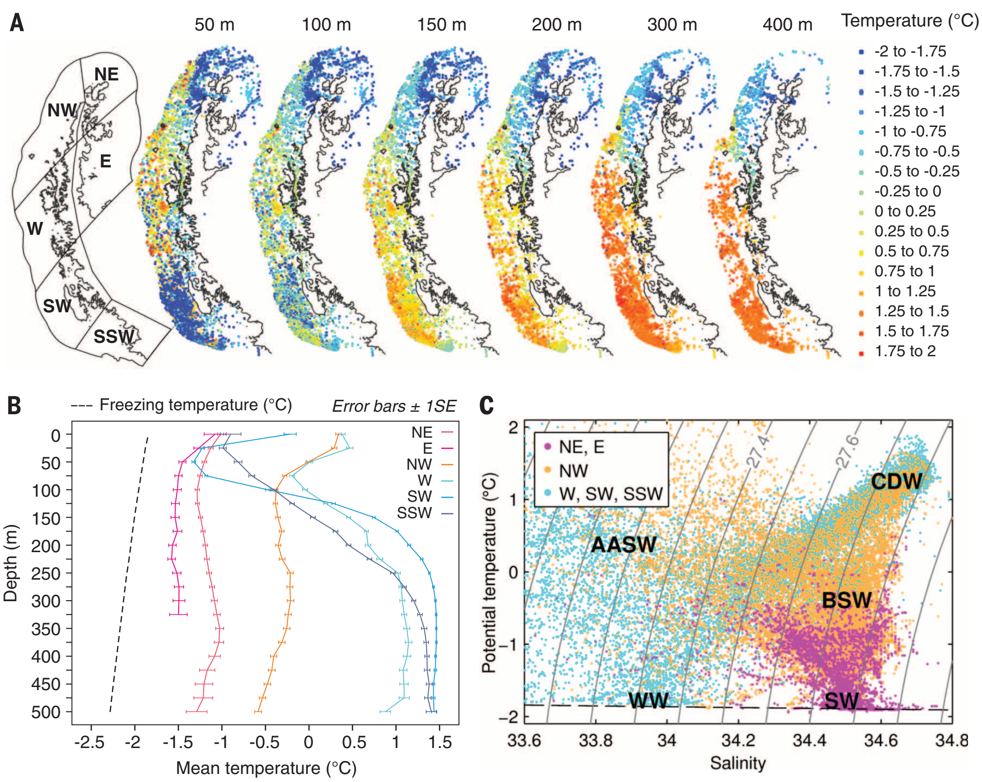

Fig. 2. Ocean conditions surrounding the AP. (**A**) In situ temperature of the ocean surrounding the AP at specific depths. The six regions are defined by east/west and by two-degree latitudinal bands, up to 100 km off the AP coast. (**B**) Mean in situ temperature profile in each region. The dashed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

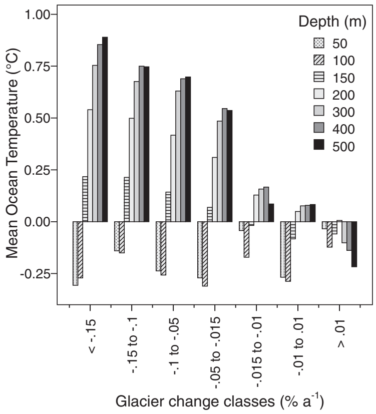

Fig. 3. Mean overall glacier changes (binned) and mean in situ ocean temperature (within 5 km of glacier fronts) at specific depths. Negative glacier change values signify retreat. The *x* axis reads from largest retreat rates on the left toward small changes and advances on the right.

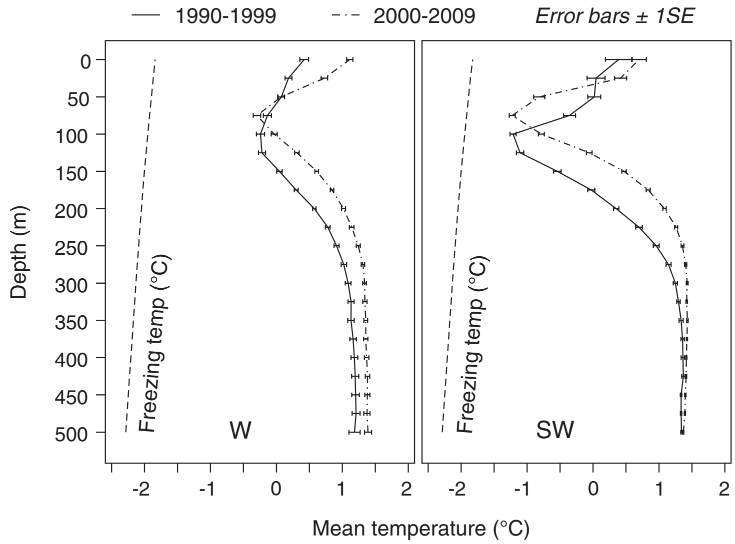

Fig. 4. Mean in situ temperatures during the 1990s (solid line) and 2000s (dot-dash line) for repeated measurements in the west (W) and southwest (SW) regions. The measurements were taken during cruises that occurred in the austral summer, with spatial coverage spanning the two regions.

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 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 farther north, however, originates in a different climatic regime from 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 before 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 southwest region (Fig. 4). During the late 1990s, a universal acceleration in glacier retreat occurred, apparent in all coastal regions except in the northwest (*8*) (fig. S2). The available oceanographic observations are therefore consistent with our hypothesis of ocean-driven glacier retreat.

We conclude that ocean temperatures below 100-m depth have been the predominant control on multidecadal glacier front behavior in the western AP. Glaciers abutting the warm, and warming, CDW regions in the Bellingshausen Sea have retreated, whereas those discharging into cooler BSW in the 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 to 300 m) in these regions. Most important, ocean warming has occurred concurrently with a widespread acceleration in glacier retreat.

Ice shelves farther 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 farther north. Indeed, the climatic setting and marine-terminating nature of these AP glaciers mean that 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 past 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 AP. 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/content/353/6296/283/suppl/DC1
Materials and Methods
Figs. S1 and S2
Table S1
Database S1
References (*33*)

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EVOLUTIONARY COGNITION

Ducklings imprint on the relational concept of "same or different"

Antone Martinho III* and Alex Kacelnik*

The ability to identify and retain logical relations between stimuli and apply them to novel stimuli is known as relational concept learning. This has been demonstrated in a few animal species after extensive reinforcement training, and it reveals the brain's ability to deal with abstract properties. Here we describe relational concept learning in newborn ducklings without reinforced training. Newly hatched domesticated mallards that were briefly exposed to a pair of objects that were either the same or different in shape or color later preferred to follow pairs of new objects exhibiting the imprinted relation. Thus, even in a seemingly rigid and very rapid form of learning such as filial imprinting, the brain operates with abstract conceptual reasoning, a faculty often assumed to be reserved to highly intelligent organisms.

Relational concepts, such as "same" and "different," have been demonstrated in a few animal species, typically after extensive training (*1*, *2*). Relational concepts differ from other forms of categorical generalization. For instance, pigeons and bees can be trained to discriminate whether novel images contain humans or not (*3*), or whether novel paintings are by Monet or Picasso (*4*), by relying on the similarity between features of the training and of the novel stimuli. In relational concept learning, however, relative properties between training stimuli generate the relationship that has to be generalized to sets of novel stimuli (*5*).

The relations of "same" and "different" have been used to study relational concept learning in a few primates and birds (*6*), using a variety of protocols. For instance, in the identity matching to sample (IMTS) protocol, an animal sees a sample stimulus and subsequently chooses between two test stimuli, one of which is identical to the sample. Reinforcement can be contingent on responding to the identical one ("same") or to the alternative ("different"). Honey bees can learn this discrimination and even transfer a correct response to novel stimuli across sensory modalities (olfaction and visual texture) (*7*). The IMTS task requires learning the appropriate comparison between the working-memory representation of the sample and the currently perceived test stimuli, but it does not require interpreting an abstract relationship between perceived items and then reapplying the same relation to discriminate between sets of novel objects.

A different procedure, that isolates relational learning, involves presenting more than one stimulus as a sample, and then selecting, from between various sets of stimuli, the set that has

Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK.
*Corresponding author. Email: antone.martinho@zoo.ox.ac.uk (A.M.); alex.kacelnik@zoo.ox.ac.uk (A.K.)

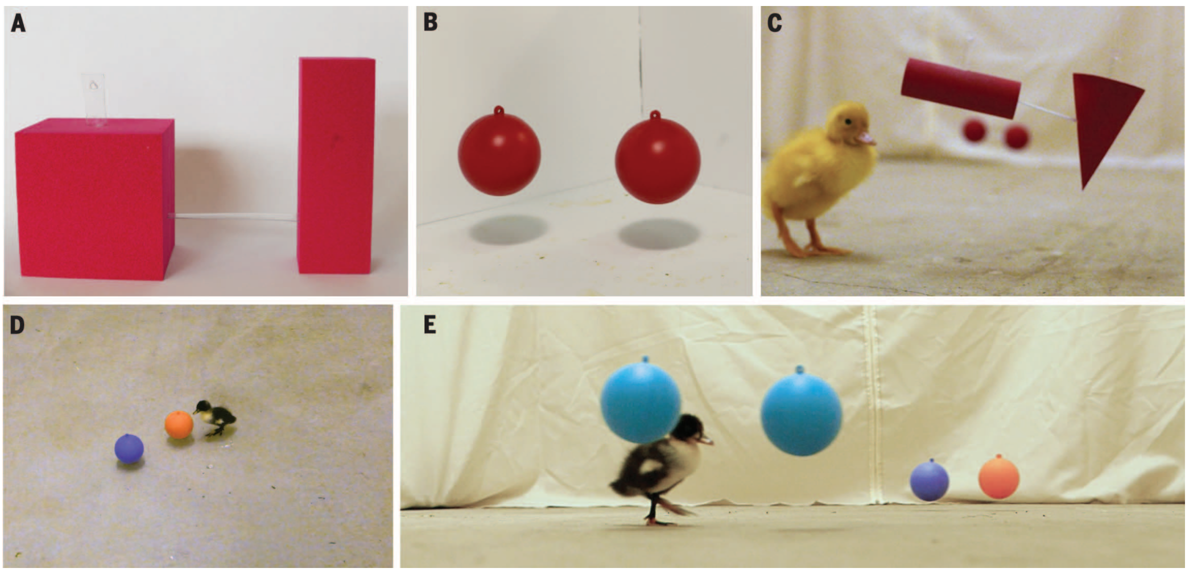

Fig. 1. Imprinting and testing stimuli. Newborn ducklings were first exposed to a pair of objects revolving about the center of a training arena, then tested with two novel pairs of objects. (**A**) Example of a "different shape" training stimulus pair. (**B**) Example of a "same color" training stimulus pair. After this exposure, the ducklings were tested for their preference between two novel stimulus pairs revolving in apposition. (**C**) A duckling trained with the set shown in (A) demonstrates its preference for a novel "different shape"' stimulus over an also-novel "same shape" stimulus. (**D**) A duckling trained with the stimulus pair shown in (B) approaches a novel "different color" stimulus pair—an incorrect response. (**E**) The same duckling later in the same trial correctly approaches and closely follows the novel "same color" stimulus.

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Supplementary Materials for

Ocean forcing of glacier retreat in the western Antarctic Peninsula

A. J. Cook,* P. R. Holland, M. P. Meredith, T. Murray, A. Luckman, D. G. Vaughan

*Corresponding author. Email: alison.cook@durham.ac.uk

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This PDF file includes:

Materials and Methods
Figs. S1 and S2
Table S1
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Other Supplementary Material for this manuscript includes the following:
(available at www.sciencemag.org/cgi/content/full/353/6296/283/DC1)

Database S1 as Excel file

Materials and Methods

Glacier-change data

Glacier-change data were produced by digitization of glacier frontal positions from archival photographic material and satellite images (ref. 9) between 1945 and 2010. The glacier-change results for all 674 western AP marine-terminating glaciers can be found in the Supplementary Database S1. This includes overall change (both absolute area change and change relative to basin size) from first to last recorded position for each glacier; date of records within each 5-year interval since interval 1945-49; and change rates (relative to basin size) calculated across each 5-year interval (as shown in Fig. S2). The 5-yearly change rates were calculated from the area and number of months between recorded positions (up to a maximum of 15 years between dates). Where two glacier change rates fall within one time interval, a weighted average of the two values was allocated to that interval.

Oceanographic data

Oceanographic analyses were based on measurements held in the World Ocean Database 2013 (WOD13) (ref. 19). We used all available ocean temperature data (1945-2009, unless otherwise indicated), to create mean ocean fields. These measurements have been made predominantly during the austral summer when sea-ice is at a minimum. Data sources are outlined in WOD13 (ref. 19). Uncorrected conductivity data from tagged seals contained significant biases, so these data were omitted.

The number of ocean measurements made has significantly increased in recent decades; however inclusion of all measurements provides a spatial mean temperature for the ocean regimes surrounding the AP (irrespective of temporal trends).

The temperature data distribution varies considerably throughout the region. A grid based on the mean of values within a regular cell size, however, reduces the influence of data clusters and results in equal spacing where values are dense. A cell size of 5 km was chosen as most suitable for the data availability. The mean temperature values used in regional comparisons are based on the mean of the gridded values.

Measurements were considered on standard depth levels, every 25 m from the surface to 500 m. We further constrained these data to within 100 km of the AP coast, dividing the data into six regions for analysis (Fig. 2A).

Bathymetric measurements close to the western AP shore are limited, but where they do exist (ref. 33) we found ocean depths greater than 200 m within 1 km for 81% of the glaciers. The mean depth within 1 km for all glaciers with depth measurements is 321 m. Many deep bathymetric troughs are present, facilitating passage of water from deeper offshore regions (Fig. S1). Although ice thickness data at glacier fronts are currently lacking, we make the assumption that water at 200 m or below reaches the majority of ice fronts on a broad regional scale.

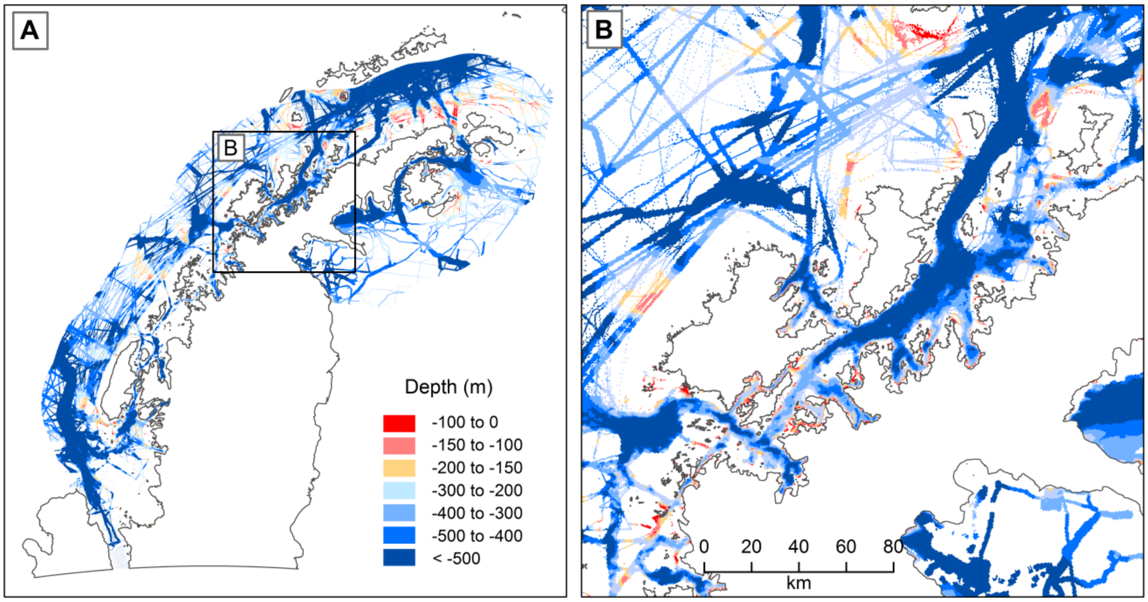

Fig. S1

(**A**) Non-interpolated IBCSO bathymetry data (ref. 34) shown at binned depths. The water column reaches depths of more than 500 m along much of the AP coastline. (**B**) Some deep troughs occur close to the shore, such as between islands and the mainland, and where ship tracks reach close to glacier fronts, many reach depths of 500 m or more.

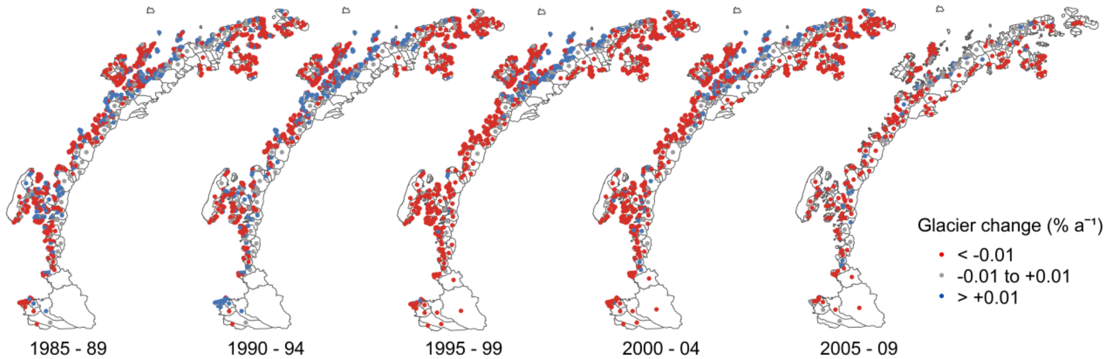

Fig. S2

Rates of change (% a^{-1}) in 5-year intervals since the late 1980s. The spatial distribution of glacier retreat shifts markedly in 1995-99: almost all glaciers are in retreat, except for those along the north-west coast, which remain stable or are advancing. An acceleration in mean retreat rates also occurred at this time.

Table S1

Correlations between ocean temperature and glacier change rate. Spearman's Rank (r_s) correlations between mean relative change rates and mean ocean temperature at each depth. Correlations marked with * are significant at the 0.01 level.

West AP: 648 glaciers	
Depth	r_s
50	0.099
100	0.037
150	-0.277*
200	-0.359*
300	-0.383*
400	-0.402*
500	-0.391*

Additional Database S1 (separate file)

Glacier area-change results for all 674 glaciers on the western Antarctic Peninsula. The data include locations, overall area measurements and 5-yearly area details for individual glaciers.

Supplementary References

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