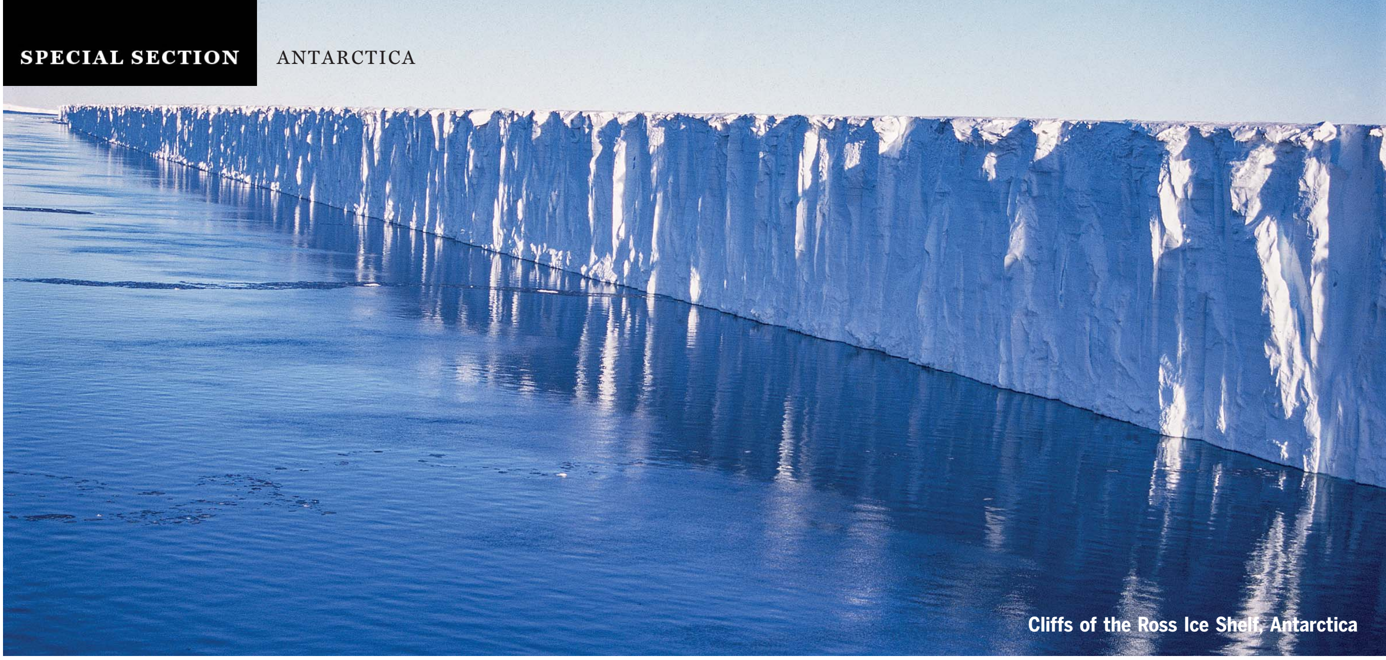

Cliffs of the Ross Ice Shelf, Antarctica

REVIEW

The Southern Ocean and its interaction with the Antarctic Ice Sheet

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The Southern Ocean exerts a major influence on the mass balance of the Antarctic Ice Sheet, either indirectly, by its influence on air temperatures and winds, or directly, mostly through its effects on ice shelves. How much melting the ocean causes depends on the temperature of the water, which in turn is controlled by the combination of the thermal structure of the surrounding ocean and local ocean circulation, which in turn is determined largely by winds and bathymetry. As climate warms and atmospheric circulation changes, there will be follow-on changes in the ocean circulation and temperature. These consequences will affect the pace of mass loss of the Antarctic Ice Sheet.

Ice shelves surround much of the continent of Antarctica. They begin where the Antarctic Ice Sheet separates from the underlying ocean floor in the southernmost reaches of the Southern Ocean. Ice shelves affect the ice sheet in a number of ways, one important one being that they can impede the flow of inland ice into the ocean and thereby slow sea level rise. In places, cavities beneath ice shelves hold relatively cold waters, helping to keep such shelves intact; other cavities contain warmer waters, threatening the existence of those shelves. Source waters for ice shelf cavities originate in the Southern Ocean, and their distribution is largely controlled by circumpolar wind patterns. Winds, therefore, dominate the interaction between the Southern Ocean and the Antarctic Ice Sheet. Future changes in wind patterns will be the principal driver of ice sheet contribution to sea level change. Understanding how winds and ocean circulation work to control the interaction between ice shelves and the surrounding waters is essential for predicting the future of the Antarctic Ice Sheet.

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Ocean–ice-sheet interaction

The direct interaction of the Southern Ocean (SO) with the Antarctic Ice Sheet (AIS) takes place largely through ice shelves. Ice shelves are the floating part of the AIS; they are formed along the coast in many locations, fed by the inland ice flowing under the action of gravity. Water is a unique substance in that its solid phase is less dense than its liquid, allowing the ice shelves to float over the surface of the ocean. On the underside of an ice shelf, interaction between the waters of the SO and the AIS leads to both melting and formation of ice and modification of the water masses in contact with the ice base. The melting itself is in part driven by another unique physical aspect of water in its solid phase: As pressure increases, the melting point drops, which means that the deeper the ice base, the greater the potential for it to be melted by ocean waters. Although the eastern portion of the AIS is largely grounded on a bed that is above current-day sea level, the opposite is the case for much of West Antarctica, meaning that a thinning in the ice could result in it going afloat, thereby leaving it vulnerable to changes in ocean temperature (*1*). The study of the interaction of the SO with the AIS is important, as the future of the AIS and global sea level are intimately tied up with the fate of the ice shelves, because the shelves serve to hold back and buttress vast amounts of inland ice (*3*), controlling its flow into the ocean [see Bell and Seroussi (*3*) in this issue].

The SO, which surrounds the AIS, is connected to the World Ocean through the Global Conveyor Belt (*4*), a planetary-scale circulation that imports warm water to the SO, modifies it in part by interaction with ice, and exports a deeper, cooler, and fresher water mass back to the World Ocean (*5*). This interaction occurs through the SO's interface with sea ice, icebergs, and ice shelves. The SO is affected by dominant westerly winds that drive an eastward ocean current that encircles the continent: the Antarctic Circumpolar Current. This, the largest current on the planet, is guided by ocean bathymetry and coastal landmass outline, and flows close to the continent in some locations and much further offshore in others. The current remains well offshore, particularly in places where there are large-scale ocean gyres (Fig. 1). Important to the interaction of the SO with the AIS is the existence of a warmer layer of water at depth beneath the surface waters. This Circumpolar Deep Water (CDW), ubiquitous at a depth centered at ~500 m, is denser than the overlying surface water despite being warmer owing to its greater salt content. Perhaps surprising, these waters largely originate at the other end of the planet, in the North Atlantic where Arctic-bound Gulf Stream waters are transformed into a water mass known as North Atlantic Deep Water, which is subsequently transported at a subsurface depth by the Global Conveyor Belt to the SO where it appears as CDW (*4*, *5*). The CDW is further modified by a seasonal cycle of sea-ice advance and retreat, which by surface area is Earth's largest such cycle. The sea-ice cycle creates a "salt-pump" that raises the salinity of the CDW (*6*). The surface waters and the CDW are vertically separated by a "thermocline," a region of strong vertical change in temperature.

Flanked by the grounded inland ice of the AIS and the deep offshore CDW of the SO lies the continental shelf, which in Antarctica is overdeepened, having an average seafloor depth of about 600 m, compared with an average of around 100 m elsewhere in the global ocean (*7*). A second distinct feature of the continental shelf is that it has a retrograde (negative) slope heading inland to the AIS in most places (*8*), in contrast to most of the rest of the world, where the slope is prograde. This reverse slope means that once an ice sheet grounded below sea level (i.e., a marine ice sheet) begins to advance over such a retrograde slope, a positive feedback begins, leading to further ice sheet growth (*9*). The opposite occurs in the case of an initial retreat [see "marine ice sheet instability" discussed by Bell and Seroussi (*3*) in this issue]. One potential trigger for an initial retreat that can lead to this instability is for more of the warm water in the SO (i.e., CDW) to come into contact with the ice shelves. Ice shelves reside over the southern reaches of the continental shelf, and for CDW to reach the sub–ice-shelf ocean cavities, it must first cross the continental shelf break, the location at which the continental shelf drops away to the deep ocean. To be able to flow onto the continental shelf, the CDW must reside in the water column at or above the depth of the shelf break. Winds and local bathymetry ultimately dictate the degree to which CDW can penetrate onto the continental shelf.

The access that CDW has to the continental shelf is greatly influenced by the winds far offshore, away from the continental shelf, that modify the depth at which CDW flows over the deep ocean. The higher in the water column the CDW sits, the greater the chance that it will cross onto the continental shelf. Over the continental shelf itself, local winds drive the cold surface waters onshore or offshore. To maintain the same water column thickness over the continental shelf, the onshore or offshore motion of the overlying surface waters forces the underlying CDW in the opposite direction. Further complicating this picture is the formation of very salty (and hence dense) shelf waters when sea ice is formed in winter by cold, southerly winds. The sea ice once formed subsequently can be blown far offshore by such winds, allowing further sea-ice formation, and thus further increasing the salinity of the water column. The dense continental shelf waters that form can block the lighter offshore CDW from getting onto the continental shelf.

In addition to wind influencing the process of whether the CDW crosses the shelf break, the bathymetry of the sea floor also affects the exchange. Because of Earth's rotation, ocean currents generally flow perpendicular to strong gradients in the seafloor depth, such as found along a continental shelf break, and they thus flow along isobaths at the shelf break. Nonetheless, the flow can cross the shelf break in particular locations; for example, at sea floor troughs cut into the continental shelf by past ice sheet advances to the shelf break (*10*). There is also a correlation between the curvature of the shelf break and the ocean flow crossing the shelf break—that is, places where the shelf break isobaths curve in front of the ocean flow. Momentum advection can force the flow across the shelf break in such locations (*11*). All these features and processes of wind and bathymetry, taken cumulatively, control the presence or absence of CDW on the continental shelf (*12*, *13*). The present-day distribution of where CDW is, and is not, on the continental shelf is shown in Fig. 1.

The properties and fluxes of the ocean waters entering a sub–ice-shelf cavity are controlled by the processes occurring over the continental shelf. Once within a cavity, the waters continue to flow along the retrograde seafloor toward the grounding zone, the region where the inland grounded ice sheet first goes afloat. When the waters reach the grounding zone, they cause melting, water mass modification, and a return flow out of the cavity. Common to all cavities is that the heat exchange between the ocean and ice is controlled by a complex boundary layer at the interface, which determines the basal melt rate of the ice shelf. The nature of the boundary layer itself depends on the stratification of the ambient water column, the level of turbulence, the strength of tidal currents, and the roughness and slope of the ice base, among other factors. The degree of melting that occurs in the various ice shelf cavities fringing the AIS can be broadly classified into two major types: low-melting in cold-water cavities (Fig. 2A) and high-melting in warm-water cavities (Fig. 2B), with the latter having modified CDW (i.e., CDW that is slightly cooler because it has mixed with another water mass) directly in

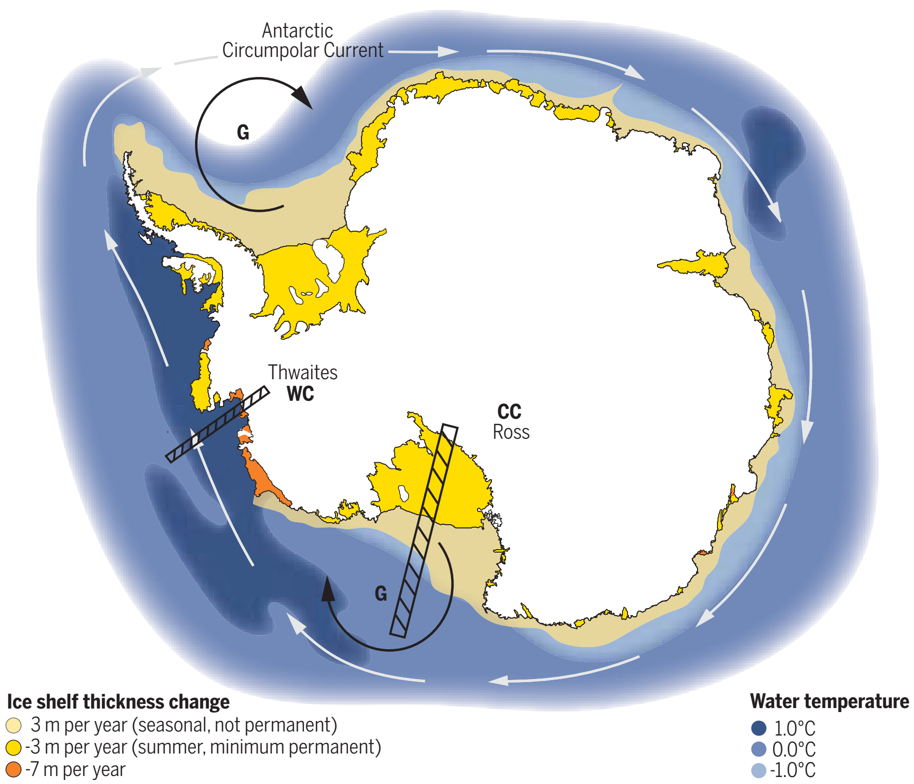

Fig. 1. Oceanographic context. Schematic illustrating the Antarctic Circumpolar Current of the Southern Ocean (arrowed white lines) encircling the Antarctic Ice Sheet. Major ocean gyres are indicated by "G". The Antarctic continent is shown as solid white, bathymetry of the continental shelf and shelf break as light yellow shading, temperature of surrounding ocean waters at 500-m depth as light blue (cold) and dark blue (warm), and ice shelves around the perimeter of the continent as dark yellow (slow basal melting) and orange (fast basal melting). Warm-water cavities occur when CDW comes onto the continental shelf; an example is Thwaites Glacier located along the transect "WC". Cold-water cavities occur where CDW does not come onto the shelf; an example is the Ross Ice Shelf located along the transect "CC".

ILLUSTRATION: N. CARY/*SCIENCE* BASED ON (*46*)

contact with the boundary layer at the ice base and the former not. Warm-water cavities are found only where the Antarctic Circumpolar Current, which carries the CDW around the SO, is located close to the continental shelf break where CDW can potentially move from offshore onto the continental shelf. By contrast, cold-water cavities are to a great extent protected from CDW by the coastal landmass outline, ocean gyres, and strong off-ice-shelf winds.

For a cold-water cavity, persistent off-ice-shelf wintertime winds cause sea ice to be formed over the continental shelf and transported away from the coast, thereby transforming the continental shelf waters into High Salinity Shelf Water (HSSW). This cold (near surface freezing point) and salty water mass is denser than the CDW that is found offshore beyond the continental shelf break. Additionally, a dynamic feature forms at the shelf break—the Antarctic Slope Front—a geophysical-fluid dynamics consequence of the presence of contrasting water masses (HSSW and CDW) adjacent to one another on either side of a strong change in bathymetry at the continental shelf break. Consequently, the HSSW effectively blocks offshore CDW from getting onto the continental shelf. The dense HSSW, which has a temperature close to the surface freezing point, floods the ice shelf cavity along the retrograde slope from the open continental shelf inland to the grounding zone. As increasing pressure lowers the melting point of ice, the HSSW is above the melting point when it encounters the ice base and therefore has the capacity to cause melting. The water mass that results from the chilling and freshening of the HSSW, known as Ice Shelf Water (ISW), has a temperature that is below the surface freezing point as a result of its interaction with ice at pressure. The added meltwater renders the ISW overall positively buoyant, and it rises along the ice shelf base, flowing back toward the ice shelf front. At some point, as it rises and the pressure decreases, the in situ freezing point increases above the temperature of the ISW, and so ice forms in the water column, accreting at the ice base to create marine ice. This melt of ice at the grounding zone and redeposition further up along the ice shelf base, and the associated movement of the water in the cavity, is known as an "ice pump circulation" (*14*).

In the case of a warm-water cavity, the absence of well-organized, off-ice-shelf winds in such a location reduces the production and off-coast transport of sea ice, and no dense HSSW is produced over the continental shelf. This in turn leads to the absence of an Antarctic Slope Front, allowing the offshore CDW to flow onto the continental shelf, forming a thermocline at the interface with the colder surface waters. The Coriolis force in the Southern Hemisphere causes moving fluid to curve to the left. The broad easterlies that blow along the coast of Antarctica therefore induce a southward transport of surface waters toward the coast, which increases the depth of the thermocline, reducing the thickness of CDW on the continental shelf. Once on the continental shelf, the CDW flows down to the grounding zone, primarily along deep sea floor troughs, and comes into contact with the ice base, causing intense melting (*15*). Despite the resultant meltwater being cooler than CDW, it is also relatively fresh and thus positively buoyant, and rises along the ice shelf base. This density-driven circulation contributes to the melting, as it results in an overall more vigorous melt-driven circulation with higher turbulence, increasing the transport of heat toward the ice base. In this setting, there is no marine ice formed at the base of the ice shelf, as the waters in the circulation are above the in situ freezing point at all depths. The inflowing CDW has far greater heat content than can be extracted by the basal melting, resulting in the vast majority of the heat content imported to the cavity being re-exported.

Currently, many ice shelves with warm-water cavities are observed from remote sensing to be undergoing rapid change (Fig. 1). Numerical models are the only predictive tool for studying the fate of such ice shelves. However, the present generation of those models demonstrate considerable uncertainty in the future behavior of the ice shelves, suggesting that the rate of retreat can vary greatly depending on the details of how melt occurs in the grounding zone (*16*). To improve numerical models, there is a pressing need for field observations to study important physical processes occurring in this critical zone, as sketched in Fig. 3 and outlined in Box 1. The change in friction when ice transitions from being grounded to floating is one such process. On the inland side of the region, where the ice is grounded, the ice experiences basal friction with the underlying bed, whereas on the other side of the region, where the ice is freely floating over the ocean cavity, the ice experiences effectively no basal friction. This transition partially regulates the volume flux of ice across

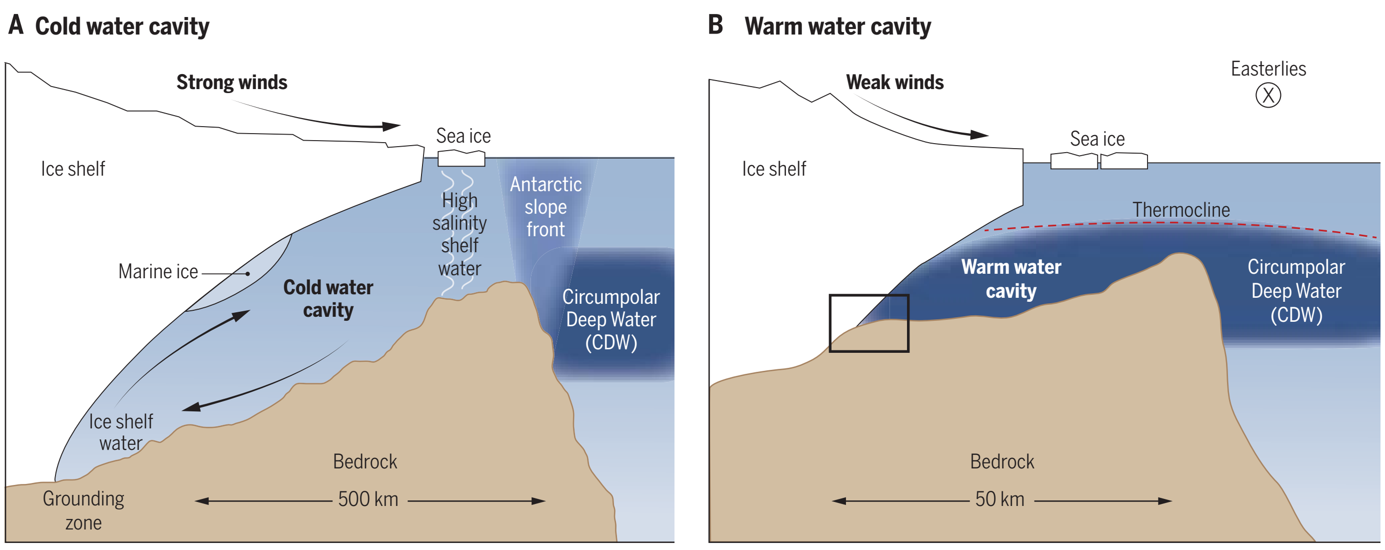

Fig. 2. Interaction of water masses with cold- and warm-water cavities. (**A**) A vertical slice illustrating the water masses interacting with a cold-water cavity (see transect CC in Fig. 1). The schematic shows a weak connectivity from (right to left) of offshore warm, circumpolar deep water (CDW) to the cold, salty water residing over the continental shelf, to the water in the ice shelf cavity, to that at the grounding zone, where the ice shelf first goes afloat. (**B**) A vertical slice illustrating the water masses interacting with a warm-water cavity (see transect WC in Fig. 1). The schematic shows the CDW on the continental shelf and entering the sub–ice-shelf cavity. Owing to the increased melt rates, the ice shelf itself (and hence the cavity) tends to be an order-of-magnitude shorter than the cold-water case shown in (A). The boxed area is described in Fig. 3.

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the grounding zone. Additionally, beneath the grounded ice, a subglacial inflow of fresh water into the ocean cavity at the grounding zone can occur, adding positive buoyancy and influencing ocean circulation in the cavity. The floating ice can also be affected by ocean tides that can lift and flex the ice shelf, temporarily moving the position of the grounding zone. Tidal currents also enhance the flow of waters in the cavity, affecting the oceanic exchange of heat at the ice shelf base.

Changes in the SO and its interaction with the AIS

Whereas ice shelf basal melt is controlled by ocean water properties, the latter are dictated by atmospheric processes. Of course, sea ice has a mediating influence on the ocean, but it is the atmosphere that dominates. On the large scale, the general circulation of the atmosphere, when viewed as an east-west average, consists of a sequence of north-south overturning cells, one of which is the Polar Cell of the Southern Hemisphere. The Polar Cell consists of descending air over the AIS but rising air over the SO (see Fig. 4A). The ascending air creates a trough of low pressure over the SO, with westerlies to the north and easterlies to the south, each driven by the pressure trough and modified by the Coriolis force.

The dominant mode of atmospheric variability for these winds in the Southern Hemisphere is the Southern Annular Mode (SAM). It is represented by a normalized index defined as the zonal pressure difference between 40°S and 65°S (*17*). SAM is then a measure of the strength of the westerlies and is known to have increased, meaning that the westerlies have been moving south and strengthening (*18*). There is decadal variability in SAM that comes from a teleconnection with the tropics (*19–21*). Additionally, SAM is strongly positively affected by ozone depletion (*22*) and greenhouse gases (*23*), implying an anthropogenic influence.

SAM is a zonally averaged index. However, if we examine the systems surrounding Antarctica without east-west averaging, we can see embedded highs and lows (see Fig. 4A). These highs and lows also exhibit strong decadal variability, largely driven by oceanic and atmospheric changes, originating in the tropics (*24–26*). These winds, whether viewed as a zonal average (as in the SAM) or with detailed east-west regional variations, influence how much and where CDW comes close to the Antarctic coast (*27–29*). Where the lows persist, the coastal easterlies are stronger than the average around the coast, forcing more surface water toward the coast by the Coriolis force. The increase in the flow of surface water to the coast decreases the amount of CDW below the surface water, and this has a tendency to lessen the amount of CDW on the continental shelf. Thus, a stronger low results in less CDW on the shelf break than a weaker low. The position of the lows also influences the ultimate amount of CDW on the shelf.

The ongoing retreat of the Thwaites Glacier system has directed much interest toward better quantifying the amount of CDW on the Amundsen Sea continental shelf. The Amundsen Sea Low, adjacent to Thwaites Glacier in West Antarctica (Fig. 1), has deepened in recent decades (*30*) and has influenced the amount of CDW beneath the Thwaites Ice Shelf (Fig. 2B). Ice cores from the West Antarctic Ice Sheet suggest that higher surface temperatures in the middle of the last century were a result of influence from the tropics (*31*). Additionally, sediment cores taken from the ocean floor in the general area suggest that a retreat has been ongoing in this area since the middle of the last century, further suggesting a tropical teleconnection (*32–35*). An analysis based on ensemble simulations from a computer model spanning the past century and looking forward through the next shows that although the winds adjacent to the Thwaites Glacier are dominated by internal climate system variability primarily from the tropics (*24*, *26*), there is a suggestion that a trend due to anthropogenic forcing is emerging (Fig. 4B) (*36*). These changing winds could have a substantial impact on accelerating the retreat of Thwaites Glacier. The Thwaites Glacier system serves as a specific and important example of how the SO interacts with the AIS and can affect its mass balance, in this case via an ice shelf with a warm-water cavity.

More broadly, the mass balance of the entire AIS is a competition between mass gain through

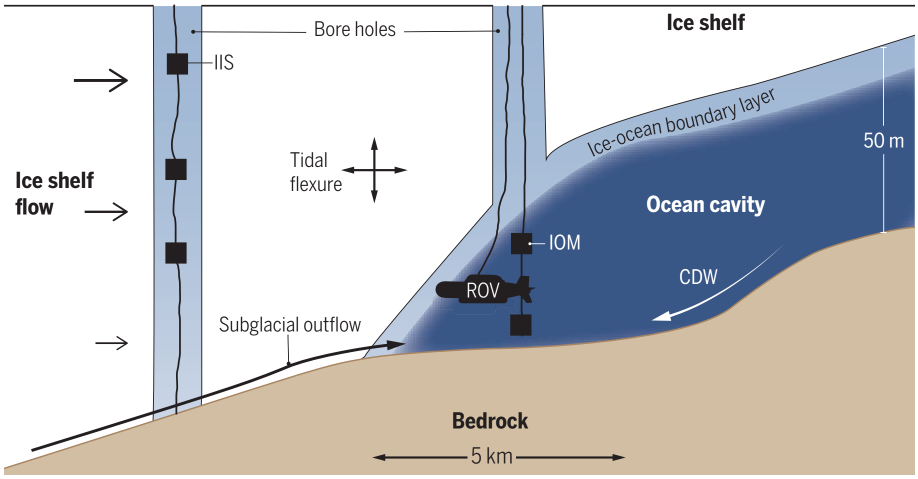

Fig. 3. Schematic showing a zoomed-in vertical slice through a grounding zone (see box at grounding zone in Fig. 2B for spatial context). The grounding zone describes the transition region where the inland ice, under the action of gravity, flowing toward the ocean, goes afloat to form an ice shelf extending out over the ocean, creating a sub–ice-shelf ocean cavity in the process.

Box 1. Observing grounding-zone processes in a warm-ocean cavity.

Physical processes at the grounding zone are not well understood, yet are critical to modeling grounding-zone change. One approach to understanding these physical processes is outlined in Fig. 3. Direct observations can be made via hot-water–drilled boreholes, both on the grounded and floating portions. On the grounded side, a down-hole instrumented ice string (IIS) can include a fiber-optic–based distributed temperature sensing (DTS) system to observe the vertical temperature profile and embedded gauges to measure shear in ice flow. On the floating side, a borehole into the ocean cavity can first allow a brief spatial exploration of the cavity, right up to the exact spot where the ice first ungrounds, using a fiber-optic tethered remotely operated vehicle (ROV) having a suite of instruments such as cameras, sensors for temperature and salinity, current meters, and side-scan sonar. Subsequently, to gain temporal information, an instrumented ocean mooring (IOM) can be placed permanently in the ocean cavity and include both a string of temperature and salinity sensors as well as turbulence gauges in the ice-ocean boundary layer. Innovations in ice and ocean instrumentation have been moving forward at a rapid pace over the past decade (*45*), allowing these types of integrated observations to be made for the first time. Although instrumentation technology has advanced, making these observations is challenged by the remoteness of the locations and the harshness of the environment (often heavily crevassed at the surface from where field camps need to be established), resulting in the planning and execution of field campaigns taking years to achieve. Such observations are presently being collected in a warm-ocean cavity by the International Thwaites Glacier Collaboration (*43*), and more will be needed both at Thwaites and elsewhere to better understand grounding-zone change.

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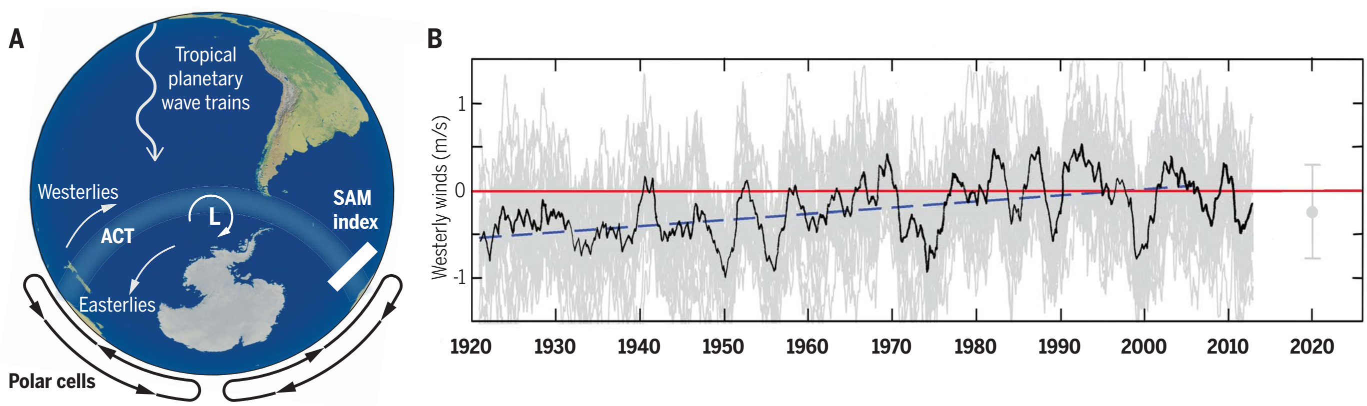

Fig. 4. Atmospheric context wind variability. (**A**) The approximately east-west oriented Antarctic Circumpolar Trough (ACT) supports a band of westerly winds to the north of the trough, and easterlies to the south. Coriolis force causes the westerlies and easterlies to drive the upper ocean waters to the north and south, respectively, creating a divergence of surface waters all along the ACT. This creates an upwelling of the subsurface CDW, which can cause it to rise above the depth of the continental shelf break in places and allow the possibility of it crossing onto the shelf and interacting with the AIS. Whether or not the CDW gets onto the continental shelf is determined by processes sketched in Fig. 2, A and B. (**B**) A time series of westerly winds in the Amundsen Sea adjacent to Thwaites Glacier (*36*). Positive values indicating westerly winds favor a greater transport of warm CDW into the cavity below Thwaites Ice Shelf, thereby increasing melting and consequently grounding-zone retreat. Negative values indicating easterly winds represent the opposite behavior. The winds were created using a global climate model that simulates large, natural, decadal variability in the climate system, principally originating in the tropics. Superimposed on this variability is a centennial-scale trend in positive wind values that is likely being forced by anthropogenic sources. The study suggests that this upward trend will lead to an increase in warm waters at Thwaites Ice Shelf, and hence increased melting and retreat.

snowfall over the continent and mass loss, the latter approximately equally split between iceberg calving and ice shelf basal melting (*37*). Under the current situation of a warming global atmosphere, AIS precipitation is likely to increase, as a warmer atmosphere can hold more moisture and therefore produce greater precipitation (*38*). At the same time, a warming atmosphere would increase surface melt of the ice sheet, leading to mass loss. Additionally, a warming atmosphere will lead to changes in wind pattens, with unknown outcomes with respect to increasingly warm ocean waters reaching ice shelf cavities and accelerating ice loss. The warm-water cavities are sensitive (*39*), as they currently have a largely unconstrained flow of warm water onto the continental shelf and into their sub–ice-shelf cavities. The cold-water cavities are currently protected by dense and saline continental shelf waters that block transport of CDW to the ice shelf cavities (Fig. 2A), although this situation could change under a changing climate (*40*). It should also be noted that the anticipated mass loss processes of surface and basal melt have an inherently faster time scale than that of the atmospheric-driven gain through precipitation. This implies that the mass loss effects may occur faster than they can be offset by precipitation.

Reductions in the extent and thickness of ice shelves and the retreat of their grounding zones associated with the ice-ocean processes occurring in cavities would have major consequences for the inland ice, causing it to flow faster to the grounding zone as the buttressing force of the ice shelves is weakened or lost (*41*). There is some evidence that the resulting reduction in buttressing produces a near-instantaneous response in the speedup of the inland ice (*42*). As the inland ice flows faster toward the ocean and is melted, the ice feeding the ice shelf becomes thinner, leading to overall decreased mass of the AIS. Of all the processes governing this mass and implied sea-level change, perhaps the most important ones are those in the grounding zone, which are also arguably the least well understood at present. This is a key motivation for the ongoing integrated field, remote-sensing, and modeling campaign called the International Thwaites Glacier Collaboration (*43*). Studies such as this into the retreat of grounding zones are needed to feed into fully coupled global climate models, so that climate models can accurately represent such processes to project future sea level with confidence [see Pattyn (*44*) in this issue].

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ACKNOWLEDGMENTS

Funding: D.M.H. and A.B. were supported by NSF grant PLR-1739003 and NYU Abu Dhabi grant no. G1204. K.W.N. is supported by NERC grant NE/S006656/1. **Competing interests:** The authors declare no competing interests. This is ITGC contribution no. 012.

10.1126/science.aaz5491

ILLUSTRATION: (PANEL A) N. CARY/*SCIENCE*

Science

The Southern Ocean and its interaction with the Antarctic Ice Sheet

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Science **367** (6484), 1326-1330.
DOI: 10.1126/science.aaz5491

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