Weddell Sea Circulation

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Introduction

Weddell Sea circulation produces the world's coldest, freshest and most oxygen-rich bottom water. This water is steered north by the Antarctic Peninsula and escapes the basin through Orkney Passage, South Sandwich Trench and Georgia Basin to replenish the deepest water mass to circulate the world's abyssal ocean, known as Antarctic Bottom Water. In contrast, Circumpolar Deep Water brings heat south, toward the Antarctic continent, and is cooled in the Weddell Gyre by surface heat loss, sea ice formation, interaction with the Antarctic ice sheet, and mixing with colder water. These processes are strongly affected by wind forcing. Both natural and human-caused changes to the winds influence the characteristics of the Weddell Sea's unique contribution to Antarctic Bottom Water.

The large-scale wind field over the Weddell Sea is characterized by westerlies in the north and easterlies in the south. These winds drive a gyre circulation that is bounded to the west by the Antarctic Peninsula, to the north by the Antarctic Circumpolar Current, and to the south by a coastline punctuated by several embayments that contain floating extensions of the ice sheet. This clockwise (referred to as *cyclonic* in the Southern Hemisphere) gyre circulation transports heat from mid-latitudes toward and beneath the floating extensions of the ice sheet. This connection between the oceans and the ice sheet is presently driving the rate of Antarctic ice sheet mass loss during ongoing climate change. Weddell Sea circulation is, thus, intrinsically important to the dynamics of ice on land and to the evolution of global sea level.

Open leads between drifting sea ice floes become hot spots for new ice formation that releases brine and increases the density of surface waters. Over the broad continental shelf in the south, this salinization of surface waters increases the density toward the west and forces deep convection that ventilates the water column. This ventilation creates a precursor to bottom water that flows down the continental slope in plumes of dense water.

Sea ice also influences ocean and atmosphere exchange. Even a thin sea ice cover can significantly reduce the heat transfer between air and water. A consolidated layer of pack ice also reduces the transfer of momentum from the atmosphere to the ocean. As the ice circulates north in the gyre, it transports fresh water to lower latitudes and, upon melting, leads to the surface freshening of the Southern Ocean in summer.

The seasonal cycle of sea ice formation and melting is dominated by atmosphere temperature, the basin scale and local wind patterns, and the balances of long- and short-wave radiation. Each of these components is influenced by natural variability as well as human-caused changes.

Topography

Weddell Sea circulation is guided by a unique combination of ridges, broad continental shelves and a northward-jutting Antarctic Peninsula that imposes a western boundary of ice and land at around 60°W (Fig. 1). Joinville Island defines the northern-most limit of the Antarctic Peninsula. To the northeast of Joinville Island, the Antarctic continent submerges to connect with the South Scotia and North Weddell Ridges that extend east. Five adjoining tectonic plates converge in this region to introduce a system of ridges and gaps (Figs. 1 and 2) that form a northern barrier to the deep and bottom waters of the Weddell Gyre. The deepest outlet for these water masses along this ridge system is through the Orkney Passage, at around 40°W (Fig. 1), where the ridge descends to ~3200 m and allows Weddell Sea Deep Water (WSDW) to escape the Weddell Sea Basin. The underlying Weddell Sea Bottom Water (WSBW) is too deep to pass through and remains within the basin (Figs. 2 and 3), flowing eastward. Some WSBW escapes via the South Sandwich Trench and Georgia Basin while the remainder circulates within the Weddell Gyre. These water masses are discussed in more detail in the Hydrography Section.

Southeast of this ridge system, a 100 km wide seamount called Maud Rise (66°S, 3°E; Fig. 1) elevates 3600 m from the sea floor. The sloping topography interacts with tides to form an anticyclonic current around the seamount that isolates the water above

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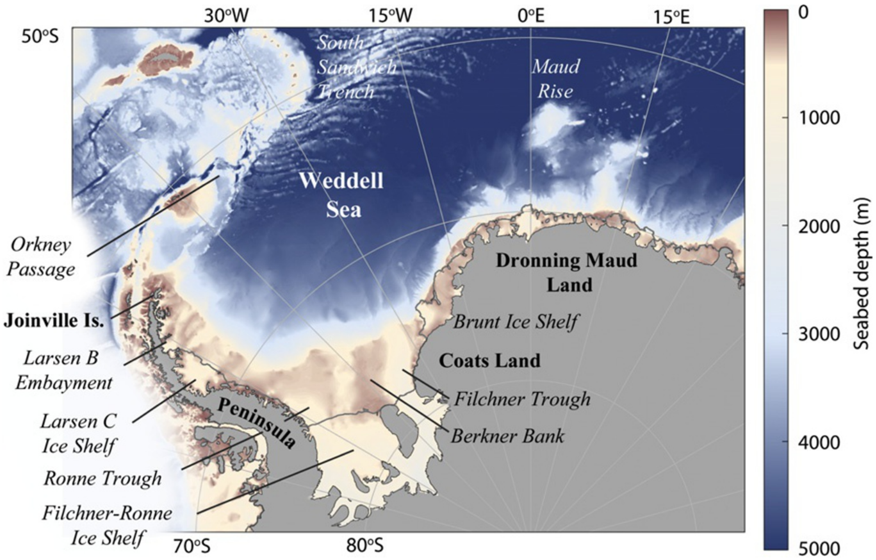

Fig. 1 RTopo-2 topography of the Weddell Sea basin. *Gray* lines over bathymetry indicate the calving fronts of ice shelves, which are the floating extensions of the Antarctic ice sheet.

within a so-called Taylor Proudman column. The core of the Taylor Proudman column is cooler and fresher than the ambient ocean with a warm halo surrounding the column and a downstream warm pool to the west-southwest. The circulation in this region supports conditions of deep convection that can, at times, introduce a heat flux to the surface ocean that melts the pack ice and creates an open water area called a polynya.

Beyond Maud Rise, the eastern extent of the Weddell Gyre is defined oceanographically by a southward propagating eddy field that populates the area around 25°E–40°E. Here, the Dronning Maud Land of the Antarctic continent connects with Coats Land to the west and helps guide the coastal current westward, toward the broad continental shelf in front of the Filchner-Ronne Ice Shelf.

Winds

The predominant wind feature around Antarctica is the polar vortex, with westerlies that drive the Antarctic Circumpolar Current (ACC). The northern limb of the Weddell Gyre is forced by these winds. This wind belt changes in strength and moves north to south over time in an oscillation referred to as the Antarctic Oscillation (AAO) or Southern Annular Mode (SAM). When the polar vortex is strong (indicative of a positive phase of the SAM) the wind belt shifts south and strengthens westerly winds to a degree that they overcome orographic blocking and carry air from the western side of the Antarctic Peninsula toward the east, across the Larsen C ice shelf. These westerlies warm adiabatically as they descend the eastern slope of the Antarctic Peninsula mountains, a characteristic that identifies them as Föhn winds.

Föhn winds introduce warmer and drier conditions to the eastern side of the peninsula and thus influence the surface melting and snow compaction of the ice shelves in this region. A positive mode of SAM also changes the wind forcing in front of the Larsen-C ice shelf. The influence of this shift in wind is most pronounced north of 70°S where the peninsula mountains become lower in elevation and are less effective at blocking westerlies. Changes in ocean circulation and air temperature as a result of this shift in atmospheric circulation have led to dramatic changes to the ice shelves on the eastern side of the Antarctic peninsula (see section Ice Shelves).

Closer to the mainland of Antarctica, winds are strongly influenced by radiational heat loss that cools the air over the continent and creates down-slope, gravity-driven flows referred to as Katabatic winds. The associated air flow can extend out over the ocean and help drive the westward flowing currents along the continent. Katabatic winds also contribute to the opening of coastal polynyas and, as a result, influence sea ice production, ocean mixing and deep-water formation.

Variability in wind forcing is both natural and human-caused. The sustained positive phase of the SAM since the 1940s has been linked to an area of reduced ozone concentrations ("ozone hole") in the Antarctic stratosphere that was created by the production of CFCs in, for example, the manufacturing of refrigerators. In 1987, the Montreal Protocol banned CFCs in this manufacturing process and 2016 marked the first year in which the ozone hole became smaller since this regulation was put in place. Although the healing of the ozone hole may influence a relaxation of the positive phase of the SAM toward neutral, increased greenhouse gas concentrations in the troposphere have a similar effect on SAM as the ozone hole and are anticipated to help contribute to sustaining a positive phase of the SAM. These anthropogenic forcings of Antarctic winds combine with natural oscillations, such as the El Niño Southern Oscillation, to introduce decadal variability and trends in wind forcing that have consequences to Weddell Sea circulation. These causes and consequences remain an area of active research.

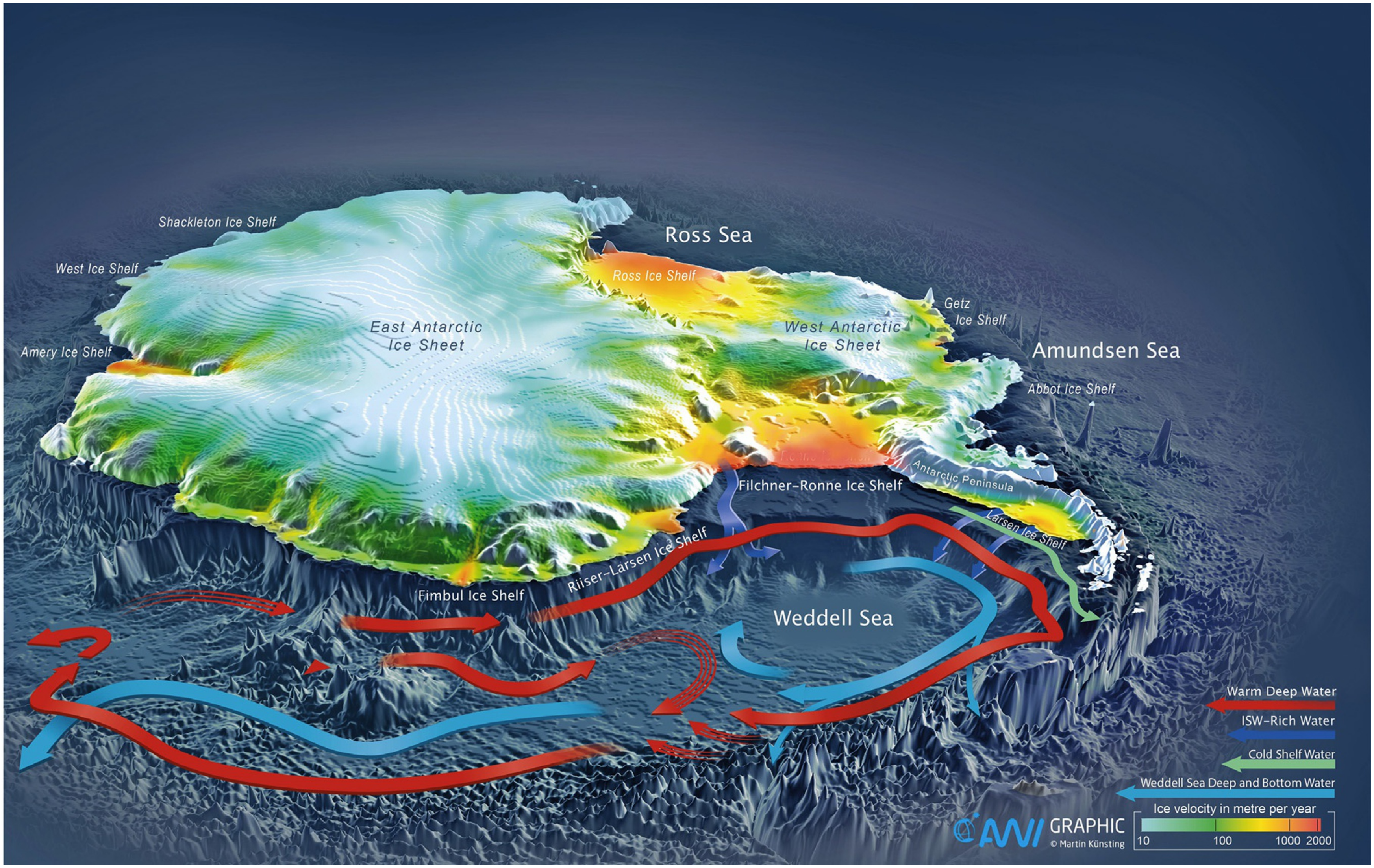

Fig. 2 Water mass circulation within the Weddell Sea Basin. *Red* arrows represent Warm Deep Water. *Dark blue* arrows represent the ISW-rich waters that flow off the continental shelf. *Green* arrows represent Cold shelf water. *Light blue* arrows represent Weddell Sea Deep and Bottom Water.

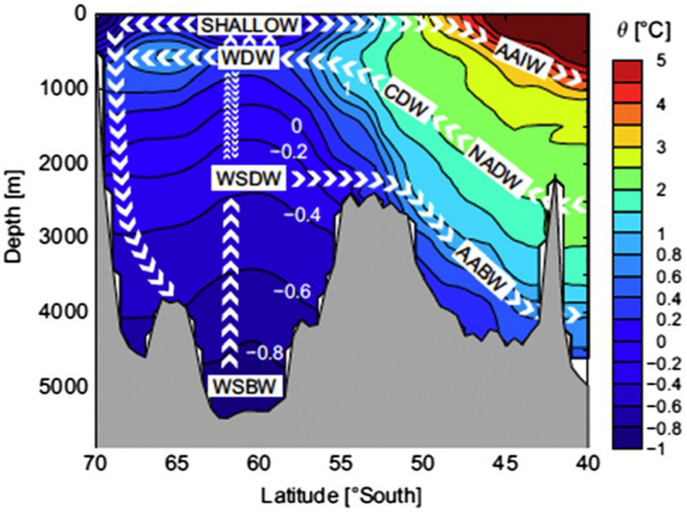

Fig. 3 A cross section of potential temperature taken along 0°E showing a vertical representation of water masses and their distribution within the Weddell Sea, as published in van Heuven et al. (2011). Their caption reads: Section along the 0°-meridian in the Southern Ocean showing potential temperature (θ) (°C) and the generalized locations and movements of various water masses. The ~45°S to ~55°S region represents the Antarctic Circumpolar Current. The 55–70°S region represents the actual Weddell Gyre, subject of this study. AAIW: Antarctic Intermediate Water; NADW: North Atlantic Deep Water; CDW: Circumpolar Deep Water; AABW: Antarctic Bottom Water; SHALLOW: the shallowest 200 m of the water column; WDW: Warm Deep Water; WSDW: Weddell Sea Deep Water; WSBW: Weddell Sea Bottom Water. This figure is published as Figure 3 of Nicholls, K. W., Østerhus, S., Makinson, K., Gammelsrød, T., and Fahrbach, E. (2009). Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. *Reviews of Geophysics* **47**, RG3003, https://doi.org/10.1029/2007RG000250

Ice Shelves

Ice streams and glaciers channel the ice from the Antarctic Ice Sheet seaward until it reaches the ocean and becomes buoyant across a ~10 km wide region referred to as the grounding line. The grounding line migrates landward and seaward with the tides as the tides lift and lower the floating extensions of the ice sheet, known as ice shelves. Ice shelves in the Weddell Sea extend 10s to 100s of kilometers over the ocean; they serve as an important connection between ocean climate variability and the Antarctic Ice Sheet because ice shelves translate changes in the ocean to changes in the cryosphere. Ice shelves gain mass from the ice streams and the accumulation of snow; they lose mass by basal melting and calving of icebergs at the ice shelf front. Changes in the extent and thickness of ice shelves affect ice stream velocities to such a degree that ice-ocean interactions is currently the primary driver of Antarctic Ice Sheet mass loss.

The largest ice shelf in the Weddell Sea is Filchner-Ronne Ice Shelf (FRIS), a 438,000 km^2 large body of ice that ranges in depth from 100 m at the terminus to ~1500 m at the deepest grounding line. FRIS accounts for 30% of the total area of ice shelves around Antarctica and is the largest Antarctic ice shelf by volume. The ice shelves to the east are much smaller (around 2000–40,000 km^2) but combine to form 210,000 km^2 of floating ice that serves an important function of freshening and cooling the coastal current that runs westward along the Dronning Maud Land.

Northwest of FRIS, five out of the six ice shelves along the Antarctic Peninsula have either retreated or collapsed since the 1940s. The most notable was the collapse of Larsen B in 2002, which resulted in up to an 800% increase in ice stream velocities between 2000 and 2003 in response to a reduced buttressing of the landward ice. This change over the Antarctic Peninsula is attributed to a southward shift in westerly winds, related to a positive phase of the SAM, that has led to atmospheric warming in this region since the 1940s. The warming trend has not extended far enough south to impact the Larsen C ice shelf to the degree that it has impacted Larsen A and Larsen B. Despite a natural calving event of the Larsen C ice shelf that released a 5800 km^2 tabular iceberg in 2017 (A-68), the Larsen C ice shelf remains stable.

Calving events release tabular icebergs that largely follow the ocean currents and provide a source of freshwater; they can also introduce a transient landscape to Weddell Sea topography, especially when the icebergs ground on shoaling bathymetry. One such calving event in 1986 released a ~3000 km^2 tabular iceberg from Filchner Ice Shelf, and a large piece of this iceberg (A-23A) has remained grounded on the eastern slope of Berkner Bank (Fig. 1). A mélange of sea ice and icebergs tends to fill in the area south of this iceberg, affecting ocean circulation and increasing sea ice concentration to the east.

Understanding changes in Weddell Sea ice shelves is important for assessing how Weddell Sea circulation influences the rate at which Antarctic ice contributes to sea level rise; but ice shelves also play an important role in cooling and freshening water masses in Weddell Sea. The cooling, in particular, is important for the formation of Antarctic Bottom Water.

Hydrography

The main source of heat and salt for water masses in the Weddell Sea is the Circumpolar Deep Water (CDW), which resides within the eastward flowing Antarctic Circumpolar Current (ACC) and has a temperature of 1–2°C and salinity of 34.62–34.73. CDW

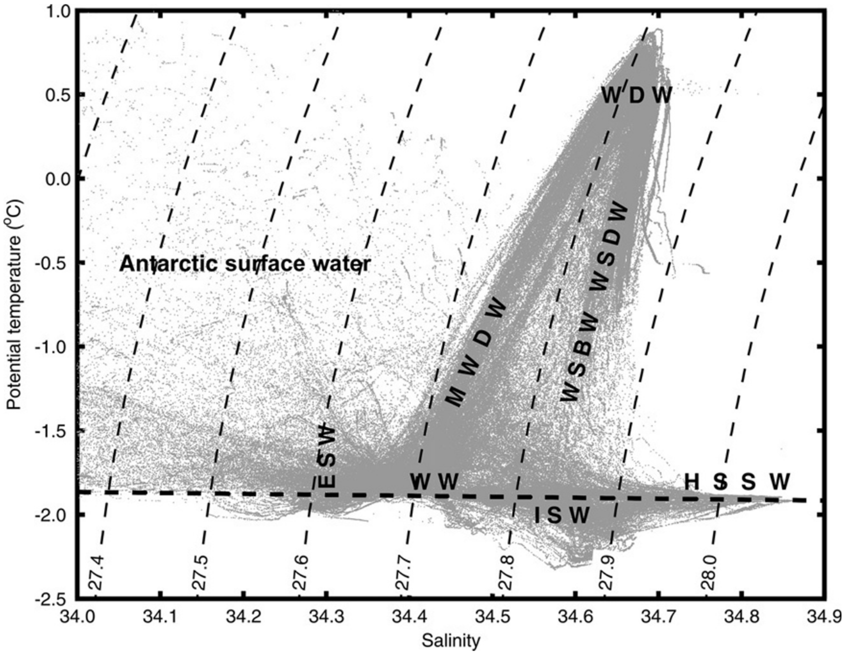

Fig. 4 A θ-S diagram showing data from 554 CTD profiles from the Weddell Sea south of 70°S and west of 0°. The diagram shows approximate θ-S characteristics for the water mass types mentioned in the text. Isopycnals are referenced to surface pressure, and the near-horizontal line shows the surface pressure freezing temperature; all data below that line are from Ice Shelf Water. This figure is published as Figure 3 of Nicholls, K. W., Østerhus, S., Makinson, K., Gammelsrød, T., and Fahrbach, E. (2009). Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. *Reviews of Geophysics* **47**, RG3003, https://doi.org/10.1029/2007RG000250.

enters the Weddell Gyre in the northeast and is gradually cooled to a potential temperature of 0–0.8°C. Referred to as Warm Deep Water (WDW, Fig. 4), this water mass extends over most of the Weddell Sea deep ocean basin, between depths of 100–1500 m, and is transported southward toward the continental shelf areas by the large-scale Weddell Sea circulation.

The water with the lowest density, thus residing on top of the water column, is the Antarctic Surface Water (ASW). Winter winds and cooler air temperatures cool ASW to the point of forming sea ice. The crystalline structure of ice squeezes out salt and introduces briny tendrils below the sea ice that inject salt into the surface ocean. The increased density of the surface ocean forces convective overturning in the upper 100–200 m. This convection, as well as wind-driven turbulent mixing, deepens the mixed layer. In the summer, sea ice melts and freshens the top layer of ASW, so that mixed layer depth reduces to 50 m and above. Remnants of the colder and saltier water produced in the winter mixed layer persist through the summer beneath the freshened surface waters and are referred to as Winter Water (WW). Winter Water mixes with the WDW below to create an intermediate Modified Warm Deep Water (MWDW, $T > -1.7°\text{C}$, $S < 34.6$, Fig. 4) that resides between WW and WDW.

The Antarctic Slope Front distinguishes the colder, fresher water on the narrow continental shelf of the eastern Weddell Sea from the warmer, saltier WDW and MWDW. The front is established by easterly winds that drive fresh, surface water onshore and cause downwelling along the coast. The density gradient across the Antarctic Slope Front supports baroclinic instabilities that shed eddies and introduce an important source of mixing and water mass modification. The density gradient also introduces a westward current that can be difficult to differentiate from the current that is forced along the coast by easterly winds. These two currents are often described together as the Antarctic Coastal Current (ACoC). The ACoC branches near the Brunt Ice Shelf, at around 27–29°W. One branch continues along the continental slope while another follows bathymetric contours leading into the Filchner Trough.

At this southernmost extent of the Weddell Gyre, WDW circulates below the 600 m sill of Filchner Trough, while the overlaying MWDW is guided onto the shelf and into the Filchner Trough that leads toward FRIS. The pulsing of MWDW onto the continental shelf is affected by the easterly winds coming off the continent. These easterlies thus introduce an influence from atmospheric variability on ocean heat transport across the continental shelf break in the southwestern Weddell Sea.

Compared to other regions around Antarctica (particularly the Amundsen Sea), mixing and recirculation across the wide continental shelf in the southwestern Weddell Sea insulates FRIS from the warmer, off-shore derivatives of Circumpolar Deep Water. Sea ice formation and brine rejection increase the salinity of the shelf water as it circulates westward. The shelf water is salinized to $S > 34.7$ and is referred to as High Salinity Shelf Water (HSSW, Fig. 4) by the time the water reaches the Ronne Trough, which cuts across the western side of the continental shelf. HSSW has a temperature of around $-1.9°\text{C}$ and is a key source for deep and bottom water formation. Some of it enters the FRIS cavity through the Ronne Trough and contributes to a counter-clockwise circulation within the cavity that generates Ice Shelf Water (ISW, $T < -1.9°\text{C}$, Fig. 4). The deep grounding lines of FRIS support melting from this very cold water because the pressure at around 1500 m in these regions reduces the freezing point temperature by over 1°C. Ocean heat melts ice according to the difference between the ocean temperature and the freezing point temperature at the ice-ocean boundary; so this reduction in the freezing point due to pressure introduces a thermal forcing that drives melting at depth for temperatures that would cause freezing at the surface. This pressure effect also means that ISW can recirculate back into FRIS and still be warm enough to contribute to further melting.

Sea ice formation and mixing across the broad continental shelf in front of FRIS combines with water mass modification beneath FRIS to create the cold and dense waters that become Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW, Fig. 3). WSDW can leave the Weddell Sea northward through topographic gaps along the South Scotia Ridge to contribute to the formation of the deepest and most ubiquitous water mass in the world's oceans, which is referred to as Antarctic Bottom Water (AABW). It is this influence of WSDW on AABW that makes it a conduit through which changes in Weddell Sea circulation are transferred into the global deep ocean.

Recent studies show that WSBW is increasing in CO_2 concentrations and becoming less dense. The increase in CO_2 is attributed to the equilibrations of surface waters with increased atmospheric CO_2, and the drawing down of these surface waters, while the decrease in density is attributed to a reduction of bottom water formation in the Weddell Sea. Changes in wind forcing, ice shelf basal melting, sea ice production, anthropogenic CO_2 concentrations and Weddell Sea circulation will play a role in the degree to which these trends continue.

To date, all water beneath FRIS is observed as being at or below the surface freezing point (-1.9°C). The freezing point reduces with increasing pressure (depth) such that thermal forcing for ice shelf basal melting is strongest at the deep grounding zones. Plumes of colder, fresher meltwater that are generated by melting in these deep regions will buoyantly ascend toward a depth that has a higher freezing point. If the meltwater plume reaches a depth where the freezing point is higher than the temperature of the water, ice platelets will begin to form and rise towards the ice ceiling where it will refreeze to the ice shelf base as a marine ice layer. This marine ice accretion is prevalent under large parts of the Ronne ice shelf base and creates a marine ice layer that is thicker than 300 m in some areas. Marine ice is important because it helps to stabilize the ice shelf by suturing bottom crevasses. Marine ice is also regarded as the origin of green icebergs. A change in source water masses under the ice shelf from cold HSSW toward the warmer MWDW would likely reduce the formation and thickness of the marine ice layer. Warmer MWDW is delivered to the continental shelf by three branching points of the coastal current, but most of its heat content is eroded as it travels over the continental shelf. MWDW with a temperature above -1.7°C (up to -1.45°C) was observed in April 2013 along the eastern side of the Filchner trough, $\sim$20 km from the FRIS cavity opening.

In climate scenario experiments, numerical models indicate a possible redirection of the coastal current with the consequence of MWDW being delivered by this eastern, Filchner Trough branch to circulate within the entire FRIS cavity by 2100. This could amplify the average basal melting at FRIS by a factor of four to six from the present day value of 90 Gt/year. Modeling studies also demonstrate that an increase in basal melting, from warmer cavity temperatures, leads to a change in the ice shelf cavity shape that introduces both positive and negative feedbacks in different regions. An increase in melting with steepening of the basal slope introduces a positive feedback between a warmer-water inflow and a change in cavity shape while the response in tide-related circulation to a change in water column thickness introduces a negative feedback to basal melting. Simulations considering all relevant effect are currently in development.

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