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### Key Points:

- Thermocline heaving and freshening of the high-density shelf water are both needed to cause a cold-to-warm regime shift in the Weddell Sea
- The presence of dense shelf water in Filchner Trough limits inflow of warm water toward the Filchner Ice Shelf front
- Reduced Filchner Trough overflow may cause increased on-shelf transport, and thus warming, in the western Weddell Sea

### Supporting Information:

- Supporting Information S1

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## Necessary Conditions for Warm Inflow Toward the Filchner Ice Shelf, Weddell Sea

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**Abstract** Understanding changes in Antarctic ice shelf basal melting is a major challenge for predicting future sea level. Currently, warm Circumpolar Deep Water surrounding Antarctica has limited access to the Weddell Sea continental shelf; consequently, melt rates at Filchner-Ronne Ice Shelf are low. However, large-scale model projections suggest that changes to the Antarctic Slope Front and the coastal circulation may enhance warm inflows within this century. We use a regional high-resolution ice shelf cavity and ocean circulation model to explore forcing changes that may trigger this regime shift. Our results suggest two necessary conditions for supporting a sustained warm inflow into the Filchner Ice Shelf cavity: (i) an extreme relaxation of the Antarctic Slope Front density gradient and (ii) substantial freshening of the dense shelf water. We also find that the on-shelf transport over the western Weddell Sea shelf is sensitive to the Filchner Trough overflow characteristics.

**Plain Language Summary** The Weddell Sea continental shelf is presently filled with water masses that are too cold to melt the Filchner-Ronne Ice Shelf from below. If warmer offshore water masses gain access to the Weddell Sea continental shelf and flow into the ice shelf cavity, the ocean-driven melting would increase rapidly and cause ice shelf thinning. Increased ice shelf melting would supply the continental shelf with freshwater that influence sea ice production and generation of dense water masses and cause an increased discharge of grounded ice, which would contribute to global sea level rise. Two main factors currently prevent warm water from accessing the Weddell Sea continental shelf. First, the warm water is located deeper than the continental shelf and does not have direct access. Second, the Weddell Sea continental shelf is filled with dense water masses that block an inflow of warmer and lighter water. We use a regional ocean model to investigate what would happen if the warm offshore water is lifted higher up or if the dense water masses become fresher and lighter. We find that the Weddell Sea system is robust, and we need to make extreme changes to both factors to allow warm water access to the continental shelf.

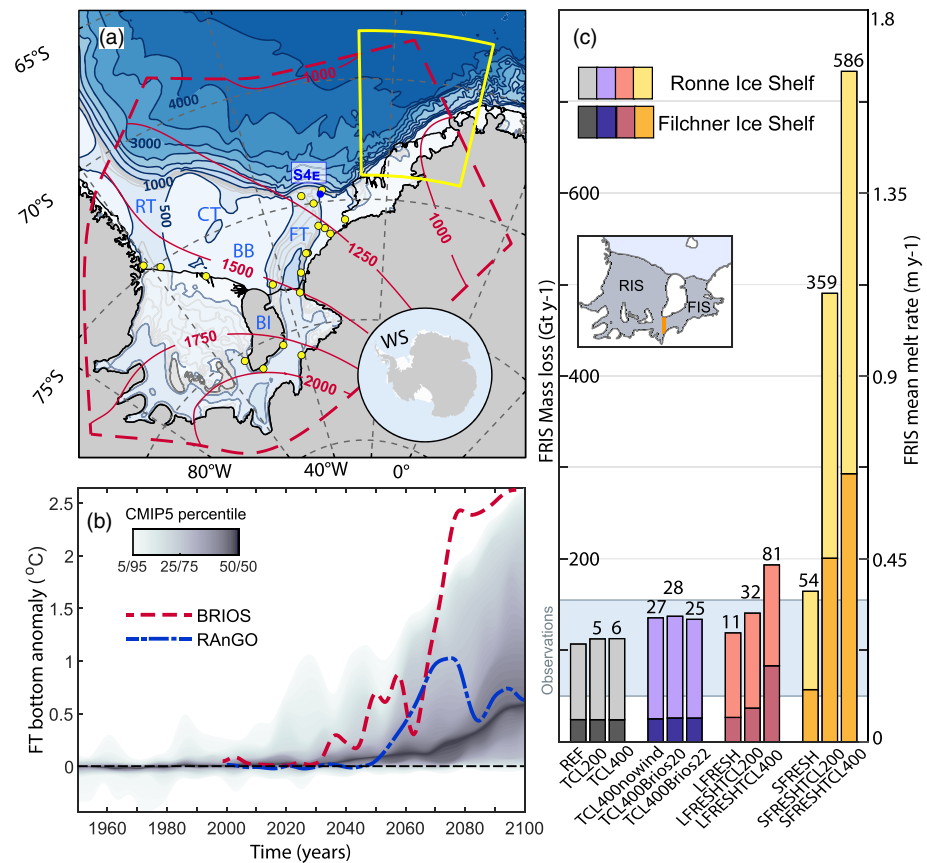
## 1. Introduction

The Antarctic ice shelves and ice sheets are thinning at an accelerating rate (Paolo et al., 2015; Shepherd et al., 2018). In West Antarctica, the observed changes are linked to increased basal melt caused by warm Circumpolar Deep Water (CDW) or derivatives thereof entering the ice shelf cavities (Jenkins et al., 2010; Pritchard et al., 2012). The risk of further ice shelf thinning and the potential for a dramatic rise in sea level accentuates the need for improved understanding of the mechanisms controlling the flow of warm oceanic water toward the ice shelves.

Today, the southern Weddell Sea continental shelf, including Filchner Trough, is dominated by cold and dense water masses. We refer to these water masses as dense shelf water (DSW). DSW is a combination of high-salinity shelf water (HSSW) and ice shelf water (ISW), where the latter fills the Filchner Trough, overflows and contributes to Antarctic Bottom Water, AABW (e.g., Carmack & Foster, 1975; Darelius et al., 2014; Foldvik et al., 2004). Warm Deep Water (WDW), the local, slightly cooler version of CDW, is separated from DSW by the Antarctic Slope Front (Jacobs, 1991; Thompson et al., 2018), located on the upper part of the continental slope. The front is maintained by persistent easterly winds and converging Ekman transport

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**Figure 1.** (a) Map showing the Weddell Sea region, the model domain (red dashed lines), the horizontal resolution in m (red contours), the region covering the observational data incorporated in the eastern boundary climatology (yellow box), and mooring locations used for validation (colored dots). Bathymetric features such as Filchner Trough (FT), Ronne Trough (RT), Central Trough (CT), Berkner Island (BI), and Berkner Bank (BB) are indicated in blue. (b) Evolution of bottom temperature in Filchner Trough in the CMIP5 ensemble models (Taylor et al., 2012), the BRIOS model (Hellmer et al., 2012), and the RAnGO model (Timmermann & Goeller, 2017). (c) FRIS total mass loss and melt rates, where shading indicates the contributions from Filchner Ice Shelf (FIS, dark shading) and Ronne Ice Shelf (RIS, light shading); the melt increase in percent, relative to REF, is indicated by the numbers on the bars. The vertical orange line in the map inset indicates the boundary between Filchner and Ronne ice shelves used in the calculations. The light blue shade indicates the observation-based range of mass loss (Depoorter et al., 2013; Moholdt et al., 2014; Rignot et al., 2013).

toward the coast of the eastern Weddell Sea (Mosby, 1934; Nøst et al., 2011; Sverdrup, 1954) and is associated with a westward flowing slope front current. Both the presence of the slope front and the presence of DSW over the Weddell Sea continental shelf and in Filchner Trough limit the access of WDW to the more southerly located Filchner-Ronne Ice Shelf (FRIS) cavity (see map in Figure 1a, Hellmer et al., 2017; Thompson et al., 2018). The basal melt rates beneath FRIS are consequently low (Depoorter et al., 2013; Moholdt et al., 2014) and relatively stable (Paolo et al., 2015) because of the cooler ocean temperatures that result from this limited access of WDW. However, weaker winds and increased surface stratification (Hattermann, 2018) cause the slope front to relax and WDW to be found at shallower depths during summer (Hattermann, 2018; Semper & Darelius, 2017). This allows for a warm seasonal inflow along the eastern flank of Filchner Trough (Årthun et al., 2012; Ryan et al., 2017), which occasionally reaches the front of Filchner Ice Shelf (Darelius et al., 2016). WDW also enters the continental shelf along a depression around 74°S, 44°W (Nicholls et al., 2008) and reaches the ice shelf front west of Berkner Island (Foldvik et al., 2001), providing a saline source for the HSSW production in the western part of the continental shelf during winter (Nicholls et al., 2009).

The WDW core in the Weddell Sea has been observed to warm and shoal since the 1980s (Schmidt et al., 2014), and the CMIP5 models project further subsurface warming in the southern Weddell Sea and

Filchner Trough (Figure 1b, Barthel et al., 2020; Taylor et al., 2012) despite lacking ice shelf cavities or related feedback processes. Simulations with a coupled ice sheet-ice shelf-ocean model (RAnGO) indicate substantial ice shelf thinning and grounding line retreat in a future climate change scenario (Timmermann & Goeller, 2017). In RAnGO, increased warm water inflow into Filchner Trough (Figure 1b) and FRIS cavity contribute to a sixfold increase in FRIS basal mass loss by 2200 (Timmermann & Goeller, 2017), which leads to 28 mm of additional sea level rise (R. Timmermann, personal communication, August 2020).

Future model projections indicate a possible tipping point behavior in the southern Weddell Sea, transforming the shelf waters from the current cold state to a warm state, with conditions similar to what we find in the Amundsen Sea today. The potential for a regime shift in the southern Weddell Sea was first proposed by Hellmer et al. (2012), who made projections for the 21st and 22nd centuries based on a coarse resolution ocean model, including sea ice (BRIOS). The regime shift was then attributed to changes in the sea ice-mediated ocean surface stress which caused a southward redirection of the coastal current. Warm water was transported into the FRIS cavity through the eastern pathway, along Filchner Trough, and caused dramatically increased FRIS basal melt rates (Hellmer et al., 2012). Further studies using a higher-resolution finite-element model (FESOM) revealed that the continental shelf salinity, which is predominantly determined by the surface freshwater flux related to sea ice formation, is important for maintaining the shelf regime and determining the rate of inflow (Timmermann & Hellmer, 2013). A positive meltwater feedback, where enhanced freshwater input from FRIS basal melt reduces the shelf salinity and further strengthens the warm inflow, may contribute to drive the system past a tipping point (Hellmer et al., 2017). These results are supported by a regional model study (Hazel & Stewart, 2020), which also suggests that offshore katabatic winds may affect the FRIS cavity circulation through modulation of sea ice formation and the freshwater flux. The uncertainties in the high-melt model studies (BRIOS and RAnGO) and the CMIP5 scenarios are pronounced (see Figure 1b), and the oceanic processes controlling the warm inflows are strongly related to the projected atmospheric forcing (Timmermann & Hellmer, 2013). All these studies are based on relatively coarse ocean model components that resolve neither the frontal processes along the continental slope and Filchner Trough nor the tidal dynamics (Stewart et al., 2019). Sensitivity studies indicate that a horizontal grid spacing of 1–5 km is required to resolve the on-shelf transport of CDW and the transport associated with mesoscale eddies (Nakayama et al., 2014; Stewart & Thompson, 2015; St-Laurent et al., 2013).

This paper addresses the knowledge gap in the dynamics behind a regime shift in the Southern Weddell Sea with model simulations that resolve the continental shelf at  $\sim 1$ -km grid spacing needed to capture shelf dynamics. We explore the question: What does it take to transform Filchner Trough from a “cold” pipeline between the ice shelf cavities and the bottom of the Weddell Sea to a “warm” one, which brings WDW from the deep ocean into the cavity where it can fuel basal melt? Based on the high-melt model studies, we have identified three potential mechanisms for increased southward transport of WDW: (i) shoaling of the thermocline over the continental slope, (ii) changes in the DSW properties reducing the blocking of WDW inflow to Filchner Trough, and (iii) changes in ocean surface stress related to reduced sea ice cover. We conduct controlled sensitivity experiments to address mechanisms (i)–(iii) using a high-resolution regional ocean/ice shelf cavity model with prescribed boundary conditions and surface forcing and a well-defined reference state which is comparable and, in part, directly derived from observations.

## 2. Model Description

We conduct regional numerical model simulations for the Weddell Sea using a terrain-following coordinate ocean model (ROMS, version 3.7) (Shchepetkin & McWilliams, 2009), coupled with ice shelf thermodynamics (Galton-Fenzi et al., 2012). The model domain consists of  $1,000 \times 800$  grid cells, where the horizontal grid spacing varies between 600 and 3,500 m (red contours in Figure 1a).

In the vertical, the model is discretized into 31 layers with an enhanced resolution near the surface and the sea bed. Sea bed and ice draft topography is based on RTopo-2 (Schaffer et al., 2016) with updates in the Filchner Ice Shelf cavity (Rosier et al., 2018). Smoothing was applied to the topography (see, e.g., Hattermann et al., 2014; Mueller et al., 2018; Zhou & Hattermann, 2020, for more detailed discussions).

We have designed a reference simulation (called REF hereafter), initialized from a time average of a 29-year-long Antarctic circumpolar ROMS simulation (Naughten et al., 2018). Idealized forcing fields of monthly climatologies were constructed for the lateral boundaries and the surface. At the northern and western boundaries, we use climatologies from Naughten et al. (2018). At the eastern boundary, we use monthly

observation-based climatologies of hydrography (adapted from Hattermann, 2018) and geostrophically balanced currents referenced to bottom current velocities from a mooring array at 17°W (Graham et al., 2013) to ensure a realistic seasonality upstream of our study area. Tides are imposed along the open boundary, by sea surface elevation changes from the major tidal constituents (M2, S2, K1, and O1 from CATS2008b, Padman et al., 2002).

Our model does not include sea ice physics or feedbacks between sea ice and shelf water properties. Instead, we restore sea surface salinity (SSS) and temperature (SST) to ensure an idealized forcing that mimics the effects of the seasonal cycle of sea ice growth and export on the density input and HSSW production in the southern Weddell Sea. This method has successfully been used to produce realistic water mass distributions on the southern Weddell Sea continental shelf (Jenkins et al., 2004), which have been identified to be important in regulating the access of WDW into Filchner Trough. While the restoring approach allows to directly assess the effect of density changes on the continental shelf, it omits the potential feedbacks at the sea ice ocean interface that may occur in a fully coupled system. We restore SSS and SST based on a combination of climatologies from Naughten et al. (2018) over the deep ocean and continental slope and synthetically derived fields that better resemble the surface conditions over the shallow continental shelf from Makinson et al. (2011). We apply surface stress from Naughten et al. (2018), which includes sea ice effects. The model is spun up over 10 years, followed by a 15-year simulation period. Estimates of the FRIS cavity exchange timescale range from 5–14 years (Huhn et al., 2018, and references therein), indicating that our simulation period of 15 years is adequate to study the FRIS melt rates and the shelf circulation. We consider that water masses on the continental shelf will typically be renewed within a decade or less (Huhn et al., 2018), but there could be feedback loops occurring on longer time scales (e.g., interaction with the Weddell Gyre or changes in the geometry of the ice shelf) that are not accounted for in this setup.

In addition to REF, we have constructed 11 simulations to study the necessary conditions for dramatic changes in the warm water inflow to the FRIS cavity. The suite of simulations is inspired by future projections from CMIP5, which show as much as a 2.5°C warming in the southern Weddell Sea (Figure 1b), and explores mechanisms (i)–(iii).

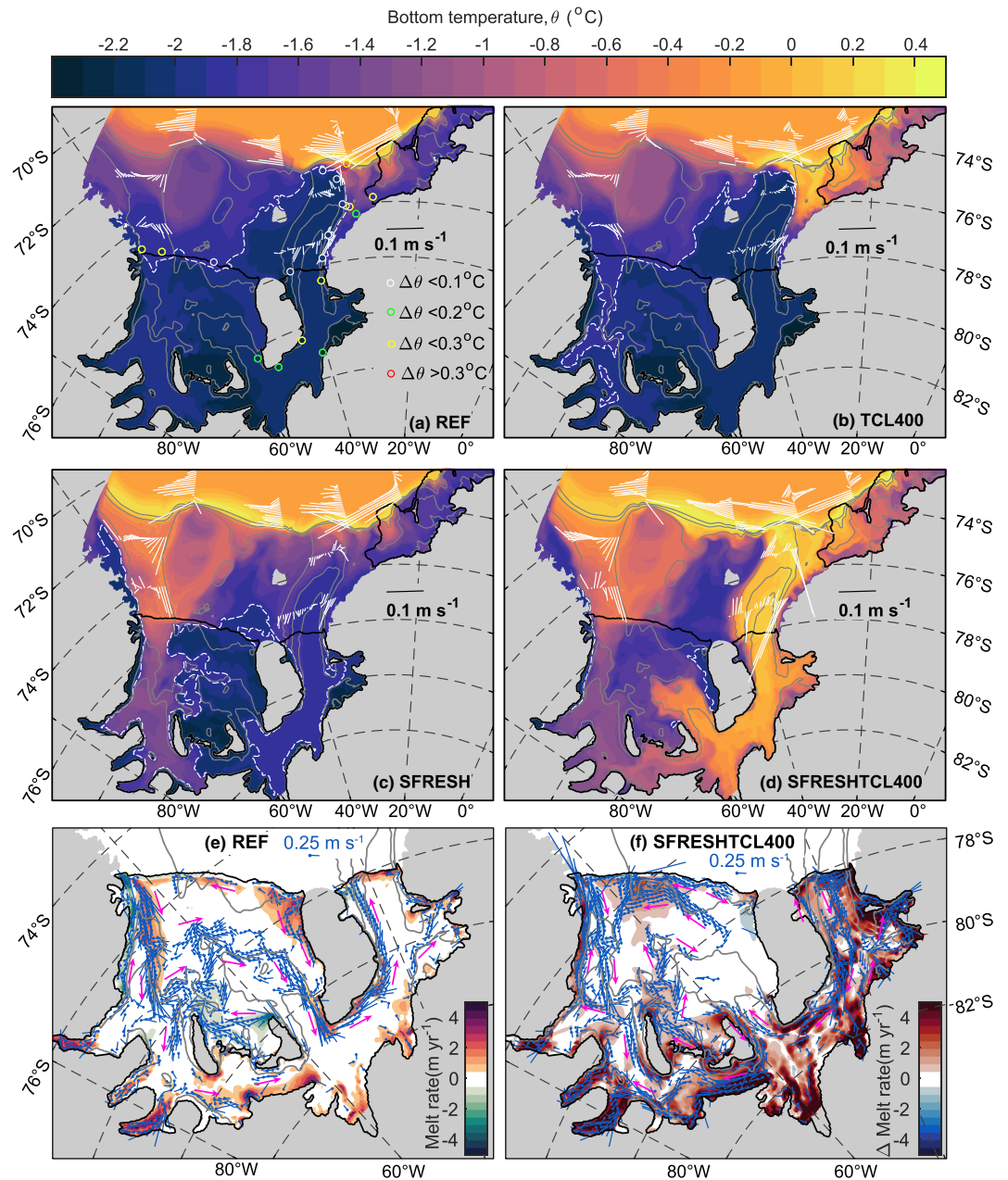
- For (i), we study the effect of thermocline shoaling along the eastern boundary continental slope by squeezing/stretching the water masses above/below the thermocline (see details in supporting information Text S1). We lift the thermocline by either 200 m (TCL200) or 400 m (TCL400).
- For (ii), we explore the long-term effect of fresher surface water over the continental shelf from reduced winter time sea ice formation. Fresher shelf water will lead to fresher and lighter DSW in the FRIS cavity and Filchner Trough. To avoid a long and computationally expensive spin-up, we choose salinity maximum cutoffs for both the surface shelf water and the DSW in the initial model field. A salinity cutoff of 34.65 (low freshening-LFRESH) results in HSSW that remains denser than the WDW offshore, but the ISW emerging from the FRIS cavity is of comparable density to the WDW offshore. A salinity cutoff of 34.4 (strong freshening-SFRESH) gives both HSSW and ISW that are lighter than the WDW (Hellmer et al., 2017). We made separate spin-ups for LFRESH and SFRESH to account for the changes in the DSW properties. Details on the construction of the salinity cutoff values and model fields are provided in the supporting information Text S2.
- For (iii), we test the hypothesis that changes in surface momentum stress can result in warmer inflow to the FRIS cavity (Hellmer et al., 2012). We have constructed two experiments where we use interpolated surface stress from BRIOS model outputs (Hellmer et al., 2012) in the 20th century (BRIOS20) and in the 22nd century (BRIOS22). These simulations are combined with the highest thermocline lift of 400 m to increase the likelihood of a warm inflow to Filchner Trough and the FRIS cavity.

### 3. Results and Discussion

#### 3.1. General Circulation Pattern and Comparison With Observations

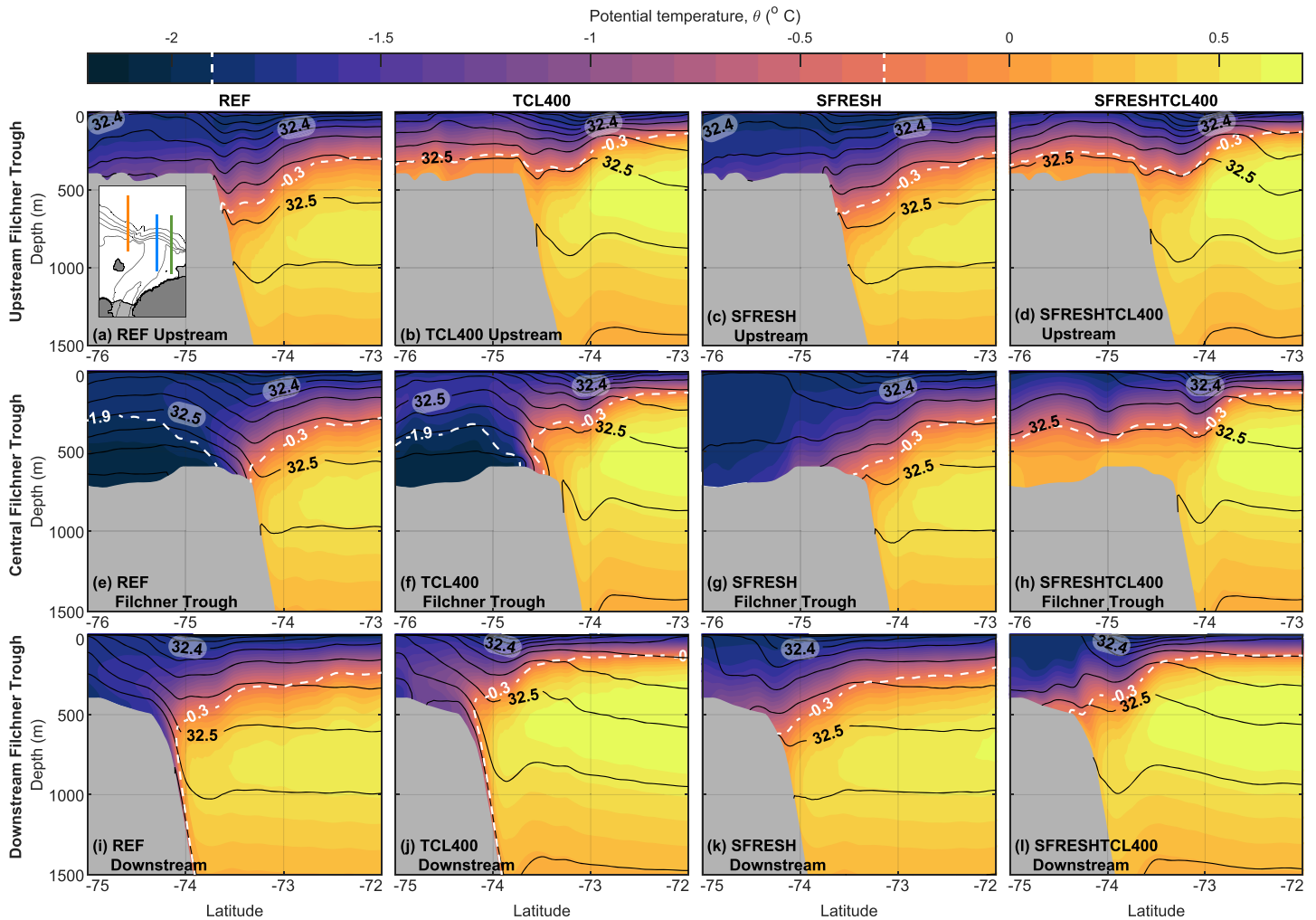
The bottom temperatures in REF agree with year-long observations (see colored circles in Figure 2a and Figures S1 and S2 in supporting information). The agreement is especially good (difference <0.1°C) in Filchner Trough. The largest discrepancy between modeled and observed bottom temperature (>0.3°C) is found at the S4E site (blue circle in Figure 1a). A warm bias is also present over the upper continental slope upstream of Filchner Trough. The bias is caused by WDW being located slightly higher in the water column in the model, compared with the observations. WDW at shallower depths should, in





**Figure 2.** (a–d) Bottom temperature (colors) and current vectors (white lines) at selected transects across the slope current, Filchner Trough, and Ronne Trough for (a) REF, (b) TCL400, (c) SFRESH, and (d) SFRESHTCL400. The current vectors represent barotropic currents calculated from the sea surface slope assuming geostrophy. The white dashed lines indicate the  $-1.9^{\circ}\text{C}$  isotherms, and the gray lines indicate the 500, 750, and 1,000 m bathymetric contours. The circle markers in (a) show bottom temperature from observations, where the circle edge colors indicate mean bottom temperature differences (model-observations). (e) Melt rates from REF and (f) melt rate anomalies, SFRESHTCL400-REF. Blue arrows in (e–f) indicate bottom current vectors, for grid cells with current speed above  $0.025\text{ m s}^{-1}$ . Pink arrows indicate the main flow directions.

principle, favor warm inflow to Filchner Trough, which means that our model is more likely to overestimate warm inflow than to underestimate it. However, there is limited warm inflow to Filchner Trough in the REF, and the majority of the warm inflow occurs over the continental shelf east of Filchner Trough. The warm water circulates on the eastern continental shelf but does not reach Filchner Ice Shelf front (Figure 2a). Although the model is biased toward warmer bottom temperatures upstream of the Filchner Trough sill, the seasonal signal is well represented upstream of Filchner Trough, with warmer water present



**Figure 3.** Potential temperature sections across the continental slope for a selection of model experiments (a–d) upstream of Filchner Trough, (e–h) at the central Filchner Trough, and (i–l) downstream of Filchner Trough. The transect locations are indicated in the map inset of (a) where the green/blue/orange bars indicate upstream/central/downstream, respectively. White, dashed lines indicate isotherms at  $-0.3^{\circ}\text{C}$  and  $-1.9^{\circ}\text{C}$ , and black contours indicate potential density anomalies  $\sigma_{\theta}$  referenced to 1,000 db.

from October to April (supporting information Figure S2). The agreement lends credibility to the observation-based climatology (Hattermann, 2018) we apply at the eastern model boundary and to the representation of the slope front dynamics in the Filchner Trough sill region.

The REF model mean state captures the dominant circulation in the southern Weddell Sea (Figures 2a and 2e). A barotropic current with maximum velocities reaching  $\sim 0.3 \text{ m s}^{-1}$  flows westward along the continental slope. The slope current core is narrow in the eastern part of the model domain where the slope is steep and widens near Filchner Trough, where the isobaths diverge. In agreement with Nicholls and Østerhus (2004), under FRIS, there is an inflow of water from Ronne Trough to the FRIS cavity, which continues east toward Berkner Island and circulates around the Berkner Island toward Filchner Trough (Figure 2e).

ISW is present in the FRIS cavity and below 200 m in Filchner Trough (Figure 2a). The low temperature in the FRIS cavity leads to low basal melt rates ( $0.24 \text{ m year}^{-1}$ , Figures 1c–2e). We infer a total FRIS basal melt mass loss of  $107 \text{ Gt year}^{-1}$ , which is within the range of estimates inferred from remote sensing ( $50\text{--}155 \text{ Gt year}^{-1}$ , Depoorter et al., 2013; Moholdt et al., 2014; Rignot et al., 2013). The spatial melt pattern in our model (Figure 2e) agrees with observations (Moholdt et al., 2014; Rignot et al., 2013), supporting our claim that the circulation under FRIS is well represented.

### 3.2. Necessary Conditions for WDW Inflow Into Filchner Trough

Our model experiments indicate that neither thermocline shoaling (i) nor DSW freshening (ii) occurring independently causes significantly increased WDW inflow into Filchner Trough and the FRIS cavity (Figure 2). The near-bottom temperature remains low despite a thermocline shoaling of 400 m (TCL400, Figure 2b), and a strong DSW freshening only causes weak near-bottom warming in Filchner Trough and Filchner Ice Shelf cavity (SFRESH, Figure 2c). The associated FRIS basal melt rates in experiments related to (i and ii) increase moderately compared to REF (5–55% increase, Figure 1c). The basal melt rates remain low when we combine a shallow thermocline with the present (TCL400BRIOS20) or future (TCL400BRIOS22) surface stress (iii).

To achieve a regime shift, where WDW flows into Filchner Trough and the FRIS cavity and induces substantially increased FRIS basal melt rates, we need to combine shallow thermocline experiments (i) with DSW freshening (ii). In agreement with Hellmer et al. (2017) and consistent with the results of Timmermann and Hellmer (2013), we find that the blocking effect of the DSW weakens when the DSW becomes fresher (LFRESH) and ceases if the DSW salinity falls below the threshold 34.4 (SFRESH), at which point DSW becomes lighter than WDW (Figure 3g and supporting information Figure S6).

In LFRESHTCL200, a warmer Filchner Trough inflow leads to higher (by  $\sim 0.1^{\circ}\text{C}$ ) near-bottom temperatures in Filchner Trough and the deepest part of Filchner Ice Shelf cavity compared to REF (not shown). The warming is more substantial (up to  $1^{\circ}\text{C}$ ) and reaches further into Filchner Ice Shelf cavity when the thermocline is lifted by 400 m (LFRESHTCL400). Here, the warm inflow contributes to a moderate increase in Filchner Ice Shelf basal melt rates (Figure 1c). The temperature in Ronne Ice Shelf cavity and the Ronne basal melt rates remain similar in LFRESH, LFRESHTCL200, and LFRESHTCL400.

When we combine a shallow thermocline with substantially freshened DSW (SFRESHTCL200-400), the WDW rises above the Filchner Trough sill depth, and the DSW barrier effect is removed. WDW freely enters the deeper Filchner Trough in this scenario, and the bottom temperature increases by up to  $2^{\circ}\text{C}$  (Figure 2d). In SFRESHTCL400, the circulation in Filchner Trough and the FRIS cavity is different from REF (Figures 2a, 2d, 2e, and 2f). WDW enters Filchner Trough from the west (not shown), crosses over to the eastern flank, and continues south toward Filchner Ice Shelf as a gravity-driven bottom current. A strong return flow is found over the western Filchner Trough. Daae et al. (2017) reported a similar circulation change in Filchner Trough in their high-resolution idealized model experiments with reduced DSW density.

In SFRESHTCL200-400, the WDW inflow reaches Filchner Ice Shelf and continues into the cavity, causing FRIS melt rate increases of 359% and 586%, respectively (Figure 1c). This increase is comparable with earlier simulations of increased melting in response to a warm temperature shift in the FRIS cavity (Hellmer et al., 2012; Mueller et al., 2018; Timmermann & Goeller, 2017; Timmermann & Hellmer, 2013). The strongest increase in melt rates occurs in Filchner Ice Shelf cavity and along the southern perimeter of Ronne Ice Shelf cavity (Figure 2f). In the FRIS cavity, the circulation around Berkner Island is reversed, that is, clockwise flow around Berkner Island (Figures 2e and 2f). The net volume transport south of Berkner Island is  $+0.73\text{ Sv}$  in REF (positive eastward), while the transports are  $-0.33\text{ Sv}$  in SFRESH,  $-0.70\text{ Sv}$  in SFRESHTCL200, and  $-0.98\text{ Sv}$  in SFRESHTCL400.

Previous model studies (Hellmer & Olbers, 1991; Timmermann et al., 2002) have suggested that the direction of the flow around Berkner Island depends on the density distribution on the continental shelf north of the FRIS edge. A counterclockwise (clockwise) flow occurs when the density maximum is located over the western Weddell shelf (north of Berkner Island), respectively. The flow reversal in our experiments is driven not entirely by the density distribution over the continental shelf but also from the density gradients in the FRIS cavity and the shut-off of the Filchner Overflow. In REF, the counterclockwise flow around Berkner Island is supplied both from the western Ronne cavity and from Berkner Bank (Figure 2e). In SFRESH, the applied salinity cutoff causes a reduction in the DSW source density that is sufficient to suppress the counterclockwise flow around Berkner Island. Instead, a clockwise flow, originating from Filchner Trough, dominates the transport between Filchner and Ronne Ice Shelf cavities. The DSW supply to the Filchner overflow shuts off. The absence of cold overflow water along the continental slope downstream of Filchner Trough allows WDW further up on the slope (visible as a continued yellow stripe along the 1,000-m isobaths in Figures 2c and 2d) and, hence, facilitates a warm inflow along the western Weddell Sea continental shelf. The warm inflow reaches the Ronne Ice Shelf cavity and further strengthens the density gradient between Filchner and Ronne Ice Shelf cavities.

### 3.3. Effects of Thermocline Shoaling, DSW Freshening, and Surface Stress Modifications

Next, we will look at details in the response to the separately imposed forcing changes related to mechanism (i)–(iii). While the limited response to changes in surface stress (iii) in our experiments does not support the mechanism proposed by Hellmer et al. (2012), we find regionally varying responses to (i) thermocline depth and (ii) DSW freshening. A shoaling thermocline mostly affects the continental shelf east of Filchner Trough, while DSW freshening leads to substantial warming over the western model domain, including the continental shelf west of Filchner Trough and the FRIS cavity (Figures 2b and 2c).

The warming of the eastern shelf in the shallow thermocline experiments (i) is related to the development of an eastward directed current over the upper continental slope, which redirects warm water from the slope current toward the eastern Filchner Trough opening and onto the shelf (not shown). On the eastern shelf, the heat content (referenced to the freezing temperature) increases by 70% (TCL200) and 172% (TCL400). The warm water is steered by topography and circulates over the eastern shelf, without entering Filchner Trough (Figure 3f) or reaching the Filchner Ice Shelf front. The associated FRIS basal melt rates are comparable to REF (Figure 1c).

DSW freshening (LFRESH/SFRESH) leads to warming in the Central Trough, the Ronne Trough, and the western Ronne Ice Shelf cavity (Figure 2c) and causes higher basal melt rates beneath Ronne Ice Shelf. The warming is likely related to the lack of a Filchner Overflow. In REF, a 100- to 300-m-thick wedge of cold overflow water is found over the continental slope (Figure 3i) and prevents on-shelf transport of WDW. A cold wedge is still present in the LFRESH simulation but occupies only the upper portion of the continental slope (not shown). In the SFRESH simulation, the wedge is absent (Figure 3k), and the increase in Ronne basal melting is stronger (30% increase in SFRESH, compared with 11% in LFRESH).

The sensitivity of the Ronne Trough warm inflow and Ronne Ice Shelf melt rates to the presence of the Filchner Trough overflow water indicates that a realistic representation of the Filchner Trough overflow is essential for obtaining realistic model estimates of present and future water mass properties and melt rates in the Weddell Sea. At the same time, the increased warm inflow along Ronne Trough in our simulations with reduced DSW salinity (LFRESH/SFRESH) will likely be sensitive to the bottom topography, which is poorly constrained over the western Weddell Sea continental shelf.

Interannual variability and short-duration storm events may influence both the preconditioning for warm inflow and the characteristics of the modified WDW available at shelf break depth. Observations from Filchner Trough suggest that a combination of a shallow thermocline over the continental slope and strong wind along the slope during storm events support southward transport of warm water toward Filchner Ice Shelf front (Darelius et al., 2016). Ryan et al. (2020) further show unprecedented fresh shelf water properties in 2017 and hypothesize that fresher shelf water upstream caused the thermocline to shoal and supported a prolonged inflow of anomalously warm and saline modified WDW into Filchner Trough. The model climatology does not contain interannual variability in the shelf/slope hydrography upstream of Filchner Trough or short-duration storm events, and we are not able to reproduce such events. However, the magnitude of this variability is expected to be small compared to the thermocline shoaling in the TCL400 experiment (e.g., the magnitude of the warm model mean state bias is comparable to the observed warm inflow event in Filchner Trough from Darelius et al., 2016), where the slope front that currently separates the shelf waters is basically flattened. As such, our simulations indicate that extreme changes of the Antarctic Slope Front upstream of Filchner Trough would be required to achieve the dramatic melt rate increase that has been found in the future scenarios of Hellmer et al. (2012).

## 4. Conclusions

Our results provide a detailed picture of the environmental settings necessary for the flow of warm water of open ocean origin onto the southern Weddell Sea continental shelf. We find that the combination of DSW properties and thermocline depth at the continental slope determines the strength and the consequences of warm water transport onto the southern Weddell Sea continental shelf. Thermocline heaving and shelf water freshening must act in concert to induce a regime shift in the sub-FRIS cavity. Thermocline heaving alone does not cause an increased inflow of warm water since the pathway along the deep Filchner Trough is blocked by the presence of DSW masses. In agreement with Hellmer et al. (2017) and Hazel and Stewart (2020), we find that the density structure in Filchner Trough is crucial for determining the water



exchange across its sill. The blocking effect decreases when the DSW becomes fresher and ceases if the DSW becomes lighter than the WDW. However, a decreased blocking effect does not lead to substantially increased FRIS basal melt rates, unless it is accompanied by a rise of the slope front thermocline far beyond the present variability to allow unmodified WDW to access Filchner Trough.

Since the density structure in Filchner Trough controls the water exchange, it is essential that models reproduce realistic DSW properties. Here, we assess the first-order response to HSSW density changes, driven by the atmosphere and mediated through sea ice response (Petty et al., 2013), in controlled experiments with surface restoring. Although further work is needed to assess the detailed response of a fully coupled system to changes in DSW properties, including feedbacks between sea ice and shelf water properties, our surface restoring approach prevents biases in DSW properties that may arise from specific sea ice models (Naughten et al., 2018). Such biases affect not only the Filchner Trough inflow but also the Filchner overflow, which in turn may affect the water exchange downstream. Our experiments suggest that a shutdown of the Filchner Trough overflow may lead to increased warm water transport into Ronne Trough, Western Weddell sea.

### Data Availability Statement

The model output files used for analysis in this paper are made available at NORSTORE (<https://www.doi.org/10.11582/2020.00055>). Synthetic fields of sea surface salinity were kindly provided by R. Mugford at British Antarctic Survey.

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