Improving Antarctic Bottom Water precursors in NEMO for climate applications

Katherine Hutchinson [1], Julie Deshayes [1], Christian Éthé [1], Clément Rousset [1], Casimir de Lavergne [1],
Martin Vancoppenolle [1], Nicolas C. Jourdain [2], and Pierre Mathiot [2]

[1] LOCEAN Laboratory, Sorbonne Université CNRS-IRD-MNHN, Paris, France
[2] Univ. Grenoble Alpes/CNRS/IRD/G-INP, IGE, Grenoble, France

Correspondence to: Katherine Hutchinson (kath.hutchinson@gmail.com)

Abstract. The world's largest ice shelves are found in the Antarctic Weddell and Ross Seas where complex interactions between the atmosphere, sea ice, ice shelves and ocean transform shelf waters into High Salinity Shelf Water (HSSW) and Ice Shelf Water (ISW), the parent waters of Antarctic Bottom Water (AABW). This process feeds the lower limb of the global overturning circulation as AABW, the world's densest and deepest water-mass, spreads outwards from Antarctica. None of the coupled climate models contributing to CMIP6 directly simulated ocean-ice shelf interactions, thereby omitting a potentially critical piece of the climate puzzle. As a first step towards better representing these processes in a global ocean model, we run a 1° resolution forced configuration of NEMO (eORCA1) to explicitly simulate circulation beneath Filchner-Ronne (FRIS), Larsen C (LCIS), and Ross (RIS) ice shelves. These locations are thought to supply the majority of the source waters for AABW and so melt in all other cavities is provisionally prescribed. Results show that the grid resolution of 1° is sufficient to produce melt rate patterns and net melt rates of FRIS (117 ± 21 Gt/yr), LCIS (36 +7 Gt/yr) and RIS (112 + 22 Gt/yr) that agree well with both high resolution models and satellite measurements. Most notably, allowing sub-ice shelf circulation reduces salinity biases (0.1 psu), produces the previously unresolved water mass ISW, and re-organises the shelf circulation to bring the regional model hydrography closer to observations. A change in AABW within the Weddell and Ross Seas towards colder, fresher values is identified but the magnitude is limited by the absence of a realistic overflow. This study presents a NEMO configuration that can be used for climate applications with improved realism of the Antarctic continental shelf circulation and a better representation of the precursors of AABW.

Plain language summary. Bottom Water constitutes the lower limb of the ocean's overturning system and is primarily formed in the Antarctic Weddell and Ross Seas due to interactions between the atmosphere, ocean, sea ice and ice shelves. Here we use a global ocean 1° resolution model with the three large ice shelves important for the formation of the parent waters of Bottom Water explicitly represented and find doing so reduces salinity biases, improves water mass realism, and gives realistic ice shelf melt rates.

1 Introduction

The Southern Ocean plays a vital role in global ocean circulation and in the storage of both heat and carbon (Marshall and Speer, 2012; Rintoul, 2018). Within this backdrop, the processes taking place adjacent to and underneath the Antarctic ice shelves are not only important for controlling regional ocean dynamics but also for facilitating globally important water mass transformations (Schodlok et al., 2015). Sea ice formation on the continental shelf decreases the buoyancy of the underlying waters through the process of brine rejection creating High Salinity Shelf Water (HSSW). When this dense water mass is formed adjacent to an ice shelf, it can follow deep bathymetric pathways into the neighboring sub-ice shelf cavity and interact with the base of the ice to form Ice Shelf Water (ISW). These dense waters then accumulate on the continental shelf and migrate towards the shelf break to cascade down the continental slope as a gravity current (Gordon, 1986; Whitehead, 1987). As the waters descend towards the depths, they mix with and entrain ambient water masses until they reach either a density neutral depth, or the sea floor, at which point they spread outwards as Antarctic Bottom Water (AABW) (Bergamasco et al., 2003; Huthnance 1995). AABW plays a crucial role in the global overturning circulation, in abyssal ventilation and in the cross-basin transport of heat, salt, carbon, nutrients and numerous other tracers (Killworth, 1983; Johnson, 2008; Orsi, 2010). The principal locations for the formation of the source waters of AABW are the Weddell and Ross Seas adjacent to the large ice shelves (Orsi et al., 1999; van Caspel et al., 2015; Kerr et al., 2018; Bowen et al., 2021).

Filchner Ronne Ice Shelf (FRIS) is located at the southern boundary of the Weddell Sea and represents 28% of the total Antarctic ice shelf area (Fig. 1b). Traditionally FRIS has been viewed as having the greatest contribution to AABW by forming the coldest and most oxygen-rich dense waters in the Southern Ocean (Nicholls et al., 2009; Naveira Garabato et al., 2002). Observations for the southern Weddell Sea continental shelf indicate that HSSW enters the FRIS cavity following the Ronne Depression (Fig. 1b), circulates under the cavity causing melting at the base of the ice shelf at great water pressures and then exits as colder and fresher ISW via the Filchner Trough (Nicholls et al., 2001; Nicholls et al., 2004; Janout et al, 2021). This outflowing ISW mixes with HSSW formed on the shallow continental shelf adjacent to Berkner Island and cascades down the continental slope, mixing with ambient modified Circumpolar Deep Water (CDW) to form AABW (Fahrbach et al., 1995; Nicholls et al., 2009).

While the main formation site of the source waters of AABW in the Weddell Sea is the FRIS continental shelf, Larsen-C Ice Shelf (LCIS) is also thought to play an important role. Nestled into the arc of the Antarctic Peninsula (Fig. 1b), processes adjacent to this ice shelf produce a fresher variety of dense water called Weddell Sea Deep Water (WSDW), which is lighter than the Weddell Sea Bottom Water (WSBW) formed further south (Fahrbach et al., 1995; Gordon et al., 2001). This water mass is less hindered by bathymetric constraints so that it is more easily transported out of the gyre over the South Scotia Ridge to make a valuable contribution to AABW (Abrahamsen et al., 2019; van Caspel et al., 2015).

The Ross Sea, the second largest site for AABW formation, is home to Antarctica's largest ice shelf representing 32 % of the total Antarctic ice shelf area (Rignot et al., 2013). The Ross Ice Shelf (RIS) is located at the southern boundary of the Ross Sea (Fig. 1a) where the continental shelf has very irregular topography with numerous troughs and depressions that act as reservoirs for dense waters (Budillon et al., 2003). Just offshore, CDW flows largely un-modified within the Ross Gyre and mixes with the local waters at the shelf break (Fig. 1a), providing a source of heat and making this a region of dynamic water mass exchange (Bergamasco et al., 2003; Budillon et al., 2003). Two recurring ice-free zones are the principal formation sites for HSSW in the area: one located at the south-western corner of the Ross Sea called the Terra Nova Bay polynya and another in front of RIS called the Ross Sea Polynya. This HSSW then spreads both northwards towards the shelf break and southwards under RIS (Fig. 1a). Similarly to FRIS, the HSSW flowing into the RIS cavity interacts with the base of the ice shelf to form ISW (Jacobs et al., 1979).

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75 While freshwater input to the ocean from ice shelf melt is (at present) relatively small in magnitude, it exerts a strong
76 modulating effect on dense water formation and Southern Ocean water mass transformation (Schodlok et al., 2015; Jeong et
77 al., 2020). The impacts of increased meltwater in a warming climate could, in addition to raising sea level, actually reduce
78 AABW formation with major consequences for global overturning (Silvano et al., 2018). One possible series of events
79 common to simulations by the E3SM, CSIRO Mk3L and LOVECLIM climate models describes how surface freshening
80 from ice shelf melt would increase stratification along the Antarctic coast, inhibit full depth convection and the formation of
81 dense shelf water, and simultaneously trap warm water at depth resulting in further ice shelf melting and a horizontal
82 propagation of the warming signal (Jeong et al., 2020; Phipps et al., 2016; Menviel et al., 2010).

83

84 Despite the importance of ocean-ice shelf interactions for the climate system, none of the models contributing to the DECK
85 experiments of the Coupled Model Intercomparison Project Phase 6 (CMIP6, used to inform the Intergovernmental Panel on
86 Climate Change (IPCC) assessment report 6 (AR6)) explicitly represented circulation within sub-ice shelf cavities (Heuze et
87 al., 2021). This has lowered confidence in projected trends for the Southern Ocean and has limited our ability to incorporate
88 the impacts of global ocean warming on the Antarctic Ice Sheet (Meredith et al., 2019; Beadling et al., 2020; Comeau et al.,
89 2022). In most coupled climate models, the formation of dense water is poorly represented as AABW is formed via open
90 ocean convection, often with mixed layers that are too deep, and polynyas that are too large and too frequent (Heuze et al.,
91 2013; Mohrmann et al., 2021). In reality, deep open-ocean convection events able to produce AABW are rarely observed
92 (Goosse et al. 2021) and instead ocean–sea-ice–atmosphere interactions adjacent to the Antarctic ice shelves are responsible
93 for the creation of the majority of AABW source waters.

94

95 The authors propose that the path towards improving AABW realism in coupled climate models starts with a more accurate
96 simulation of the dense precursors on the Antarctic continental shelf. Then work needs to be done on improving the
97 overflows so as to facilitate the downslope export of these waters, and on decreasing the strength of open ocean convection
98 (Heuze et al., 2021). The Nucleus for European Modelling of the Ocean (NEMO) model is used as the ocean component in
99 many climate models (Hazeleger et al., 2010; Scoccimarro et al., 2011; Hewitt et al., 2011, 2016; Dufresne et al., 2013;
100 Voldoire et al., 2013; Cao et al., 2018; Swart et al., 2019) and consequently the development of configurations with
101 improved realism of Antarctic shelf water circulation and AABW source water properties is of interest to a large community.

102

103 Ice shelf melt has previously been represented using NEMO in a variety of ways: prescribed using a freshwater flux at the
104 surface, a fixed flux distributed over the depth range of the mouth of the ice shelf front, a specified melt at the base of the ice
105 shelf, and an interactive melt with both fixed geometry and evolving coupled ice shelves (Mathiot et al., 2017; Storkey et al.,
106 2018; Smith et al., 2021). The simulations with a fixed freshwater flux parameterisation at depth perform well in terms of
107 mimicking the vertical overturning and associated entrainment of ice shelf melt. This representation, however, is limited by
108 its inability to produce the horizontal variability observed adjacent to large ice shelves and it does not allow for interactive
109 ice-ocean exchange that evolves with ocean properties. For this, it is necessary to allow for circulation underneath the ice
110 shelf (Mathiot et al., 2017; Storkey et al., 2018; Comeau et al., 2022). Of all the previous studies using NEMO
111 configurations with explicit sub-ice shelf cavities, only one has been at a resolution that is compatible with long-term climate
112 projection applications, that developed by Smith et al. (2021) where a global ocean 1° NEMO (eORCA1) is coupled with
113 interactive ice sheets in the the U.K. Earth System model (UKESM). Previous studies have proven very useful in illustrating
114 the strengths and weaknesses of NEMO's representation of ocean-ice shelf interactions but the results apply to regional
115 configurations (e.g. Mathiot et al., 2017; Jourdain et al., 2017; Hausmann et al., 2020; Huot et al. 2021) or high resolution
116 global configurations (e.g. 1/4° and 1/12° in Storkey et al., 2018) and so do not fit the needs of typical CMIP models. The
117 results presented by Smith et al. (2021) for UKESM with NEMO eORCA1 coupled to an Antarctic ice sheet model highlight

118 the substantial advancement in model development, but do not show how this coupling affects the realism of Southern Ocean
119 water mass properties and dynamics. Evaluation of the initial state of the UKESM (NEMO coupled to BICYCLES ice sheet
120 model) was undertaken by Siahaan et al. (2021), but the investigation served to check for the absence of large biases and so
121 an in-depth comparison was not carried out.

122

123 A gap therefore exists to take a step-by-step approach to represent ice shelf-ocean interactions in NEMO for climate
124 applications. Additionally, a well documented description of one possible method to simulate sub-ice shelf cavity circulation
125 in low resolution ocean models could be of use in the designing of the next phase of CMIP. In this study we present the first
126 proposed step in this journey by explicitly simulating circulation under only Ross Ice Shelf (RIS), Filchner-Ronne Ice Shelf
127 (FRIS) and Larsen C Ice Shelf (LCIS). We choose to keep all other ice shelves closed with prescribed melt rates injected at
128 the mouth of the front using the method described by Mathiot et al. (2017). RIS, FRIS and LCIS were chosen due to their
129 role in the formation and setting of properties of the parent waters of AABW (Kerr et al., 2018; Bowen et al., 2021), and due
130 to their large size and thus practicality of realistically simulating their sub-ice shelf cavities in a global ocean 1° setup. We
131 choose to explore the changes in circulation, melt rates, and water mass properties in a forced scenario with fixed cavity
132 geometry as coupling can introduce further biases and obscure the changes attributed to sub-ice shelf circulation. By taking
133 this circumspect approach it is possible to diagnose the impact of ocean-ice shelf interactions on the parent waters of AABW
134 and produce a validated configuration of NEMO that can either be used for the next generation of climate models or as an
135 interim step towards dynamic ice-sheet coupling.

136

137 The model setup, configurations used in this study, forcing, and methodology to establish initial conditions under the ice
138 shelves are described in Sect. 2. A validation of the reference configuration compared to ocean observations is presented in
139 Sect. 3. Sect. 4 then explores the results from the "Open" cavity simulation and compares melt rates and thermohaline
140 properties with other model estimates and observed values. Sect. 5 provides the reader with a discussion and Sect. 6 presents
141 a conclusion of the findings of this study. Additional information regarding sea ice, volume and density changes along with
142 an analysis of mixed layer depths in the model compared to an observational atlas are provided in Supplementary Material.

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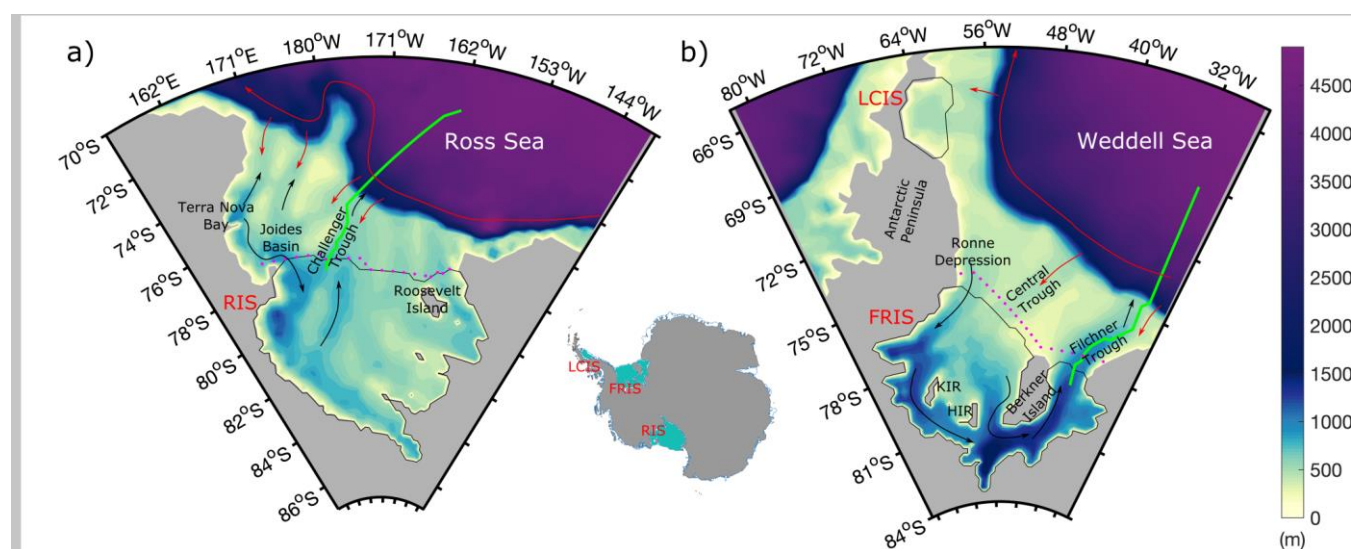
144
145 Figure 1: Model bathymetry for (a) the Ross and (b) Weddell Seas with main topographic features labeled (KIR: Korff Ice
146 Rise; HIR: Henry Ice Rise). Red arrows show direction of flow of warm deep water and black arrows indicate dense shelf

147 water circulation according to observational estimates. Circulation features depicted in this figure are adapted from
148 information presented in Budillon et al. (2003), Bergamasco et al. (2003), Russo et al. (2011) and Janout et al. (2018).
149 Magenta dotted lines indicate sections used for CTD comparisons and green lines show shelf cross sections used for analysis
150 in Figs. 8 and 9.

151 **2 Methods**

152 **2.1 Model setup**

153 For this study version 4.2 of NEMO is used (NEMO System Team, 2022). NEMO is a three-dimensional, free-surface,
154 hydrostatic, primitive-equation global ocean general circulation model. Our configuration uses the eORCA1 global grid with
155 nominal horizontal resolution of 1° at the equator and a reduction in meridional grid spacing towards higher latitudes to
156 match the accompanying shrinking of the zonal dimension of the grid cells. In the Southern Hemisphere, the model grid has
157 been extended to reach 85° S to allow for the representation of the sub-ice shelf seas according to the procedure described in
158 Mathiot et al. (2017). The average horizontal resolution of the grid under RIS, FRIS, and LCIS is 20 km, 22 km and 42 km
159 respectively. To account for the decrease in the horizontal size of grid cells at high latitudes, we decide to scale horizontal
160 eddy viscosity south of 65° S according to grid cell size. In the vertical, the configuration possesses 75 levels, with thickness
161 increasing from 1 m at the surface to 200 m at depth (Storkey et al., 2017). We use the z* vertical coordinate adapted to the
162 ice shelf so that all cells between the surface and the ice shelf base are masked at initialisation and the effect of the ice shelf
163 on friction and pressure gradient is calculated (Madec and NEMO team, 2016; Mathiot et al., 2017). The bathymetry used is
164 derived from the ETOPO2v2 data set (NOAA, 2006) with information for the extension under the ice shelves based on
165 IBSCO (Arndt et al., 2013). For the calculation of the thermodynamic properties of seawater, NEMO uses TEOS-10 giving
166 results in conservative temperature and absolute salinity which for the purposes of this study were converted to potential
167 temperature and practical salinity in order to facilitate comparison of the model results with observations and known
168 signatures of water masses. For more information regarding the choices of advection and diffusion schemes, mixing
169 coefficients, and eddy parameterizations, please refer to the copy of the namelists provided in the accompanying data
170 repository.

171
172 The ocean dynamics component, NEMO OCE, is coupled with SI^3, the dynamic and thermodynamic sea ice model of
173 NEMO (Rousset et al., 2015; Vancoppenolle et al., 2023). SI^3 is directly resolved on the ocean grid, based on an energy- and
174 salt- conserving approach for sea ice thermodynamics (Vancoppenolle et al., 2009), multiple categories to resolve subgrid
175 scale variations in ice thickness (Bitz et al., 2001; Lipscomb, 2001), a second-order moment-conserving scheme for
176 horizontal advection (Prather, 1986), and the adaptive elastic-viscous-plastic formulation for the rheology term of the
177 momentum equation (Kimmritz et al., 2016).

178
179 **2.2 Open vs Closed Configurations**
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181 Results from two configurations are presented here: first a "Closed" cavity reference configuration where ice shelf melt is
182 prescribed in a way to mimic the ice-shelf overturning, and secondly an "Open" cavity configuration. For the reference
183 "Closed" cavity configuration, a fixed freshwater flux corresponding to the volume of basal meltwater estimated by
184 Depoorter et al. (2013) for each ice shelf is added into the ocean evenly between the ocean floor and the base of the ice shelf
185 at the location of the ice shelf front and a vertical wall closes the cavity at this location (as in Mathiot et al., 2017). For the
186 "Open" cavity configuration, the majority of ice shelves are kept closed using the same method as described above and only
187 three of the largest cold-core ice shelves are opened. Circulation is simulated under RIS, FRIS and LCIS where the

188 prescribed freshwater flux is turned off at the mouths of these cavities and interactive melt is activated. Ice shelf melt and
189 freeze are calculated using the 3-equation formulation (Hellmer and Olbers, 1989; Holland and Jenkins, 1999; Asay-Davis et
190 al., 2016) in which the temperature, salinity and velocities are averaged over a fixed boundary layer thickness of 30m
191 (Losch, 2008). The top drag coefficient used is 10^{-3} and the temperature and salinity transfer coefficients used are 1.4 x 10^{-2}
192 and 4 x 10^{-4} respectively. Note that a fixed ice shelf geometry is maintained, thereby assuming a steady-state where all ice
193 melted by the ocean is replaced by the seaward advection of new ice (Schodlok et al., 2015; Mathiot et al., 2017).

195 By using this combination of explicit and parameterised ice shelf cavities, we provide an intermediate step between
196 prescribed melt and explicit cavities or even ice sheet coupling, and gain experience and a better understanding of the impact
197 on ocean dynamics in order to better inform future choices. The advantage of this approach is that it allows us to specify the
198 melt for small cavities which remain unresolved or insufficiently resolved at a 1° resolution, and simultaneously utilize the
199 model capability to resolve sub-ice shelf cavity circulation under the large cold ice shelves, which allows for more realistic
200 formation of the source waters of AABW. Figure 1 shows the extended bathymetry of eORCA1 for the Weddell and Ross
201 seas with the three ice shelf cavities of interest un-masked and important features labeled.

2.3 Forcing

205 For both "Open" and "Closed" configurations, the model was run for 124 years using 2 cycles of interannual (1948-2009)
206 CORE forcing (Coordinated Ocean - ice Reference Experiments; Large & Yeager, 2004; Griffies et al., 2009). Sea surface
207 salinity restoring is activated, but not under sea ice as we have low confidence in the sea surface salinity climatology in this
208 area due to limited observations. Freshwater discharge from iceberg melt is parameterized using a prescribed surface flux
209 (Merino et al., 2016) based on calving estimates from Depoorter et al. (2013).

2.4 Initial conditions

213 For all simulations, global ocean properties were initialized using the 1981-2010 climatology of World Ocean Atlas 2013
214 (WOA2013; Locarnini et al., 2013; Zweng et al., 2013). This climatology does not, however, extend under the Antarctic ice
215 shelves and so in order to provide somewhat realistic initial conditions underneath FRIS, LCIS, and RIS, we employed an
216 idealized regional configuration of each ice shelf. For this we created a NEMO test case using a closed domain, with
217 temperature and salinity restoring at the boundaries, 75 vertical layers and a resolution, timestep and bathymetry
218 corresponding to that of eORCA1. The domain for each of the 3 configurations included just the ice shelf and adjacent
219 continental shelf and slope and so were reasonably low-cost and fast to run in order to perform sensitivity experiments. The
220 simulations were initialized with a constant and uniform temperature and salinity and restored at the boundaries using a
221 mean profile from WOA2013 for that region. The choices for initial thermohaline properties inside the cavities were
222 informed by calculating the mean properties of detected ISW from CTD observations performed in the area adjacent to each
223 ice shelf and converting these to conservative temperature and absolute salinity for input to the model (-2 °C and 34.76 for
224 FRIS (Janout et al., 2021), -1.95 °C and 34.74 for LCIS (Nicholls et al., 2004; Hutchinson et al., 2020), and -1.94 °C and
225 34.76 for RIS (Bergamasco et al., 2003; Budillon et al., 2003). Each simulation was run for 10 years, which was found to be
226 sufficiently long to spin-up the circulation within each cavity and reach a stable melt rate. The temperature-salinity
227 distributions within the cavity were extracted and merged with WOA data re-gridded to the NEMO eORCA1 grid, with a
228 cubic spline used to smooth the data discontinuity across the ice shelf front. By following this method we have attempted to
229 provide as realistic initial conditions for eORCA1 as possible with the simulation starting with CORE forcing from the 1st of
230 January 1948.

3 Water mass realism in NEMO without cavities

To assess the existing biases in the representation of dense water properties in NEMO v4.2 eORCA1 standard configuration ("Closed"), full depth temperature versus salinity plots along with bottom temperature and salinity are compared with World Ocean Atlas (WOA 2018) gridded observations from 1981-2010 (Locarnini et al., 2018; Zweng et al., 2019) in Figs. 2 and 3 for the Weddell and Ross Seas respectively.

WOA observations indicate the presence of HSSW on the south-western continental shelf of the Weddell Sea, possessing salinities of up to 34.9 psu, likely sourced from the coastal polynya along the western flank of FRIS ice shelf front (Figs. 2a, 2c and Supplementary Fig. S3a). On the eastern side of the FRIS ice shelf front, evidence of ISW can be seen with temperatures below surface freezing point (-1.9 °C) and fresher salinities of around 34.65 psu (Figs. 2a and 2b). Results from CTD observations obtained on the continental shelf in front of FRIS propose a counter-clockwise circulation pattern with HSSW entering the cavity via the Ronne Depression and ISW exiting via the Filchner Trough (Fig. 1b; Janout et al., 2021). By comparison, the standard model configuration is overall too salty on the continental shelf with HSSW properties that are out of the bounds of the observed range (HSSW box Fig. 2d). Most notably, there is a pool of HSSW that has built up in the Ronne Depression resulting in overestimations of bottom salinity and exaggerated cool conditions on the southwestern Weddell shelf (Figs. 2e and 2f). In terms of ISW, there is none detected in the model output (ISW box Fig. 2d) as in this configuration there is no explicit ocean-ice shelf interaction. Offshore bottom temperature is overall colder than in WOA, resulting in a core AABW signature that is at the lower limit of observed values (Fig. 2d). This is indicative of the effects of strong open ocean deep convection (Heuze et al., 2021) which is highlighted in Supplementary Fig. S2c by the over-deep mixed layers in the central Weddell Gyre.

Due to the limited observations adjacent to LCIS, WOA bottom properties do not capture the cold water masses located on the continental shelf detected by Hutchinson et al. (2020), where bottom temperatures of below -2 °C and salinities of 34.6 psu were reported. Instead Fig. 2b indicates very warm conditions (temperatures of around 0.5°C) on the western flank of the Weddell Sea. The authors explored the bottom properties in this area in the Southern Ocean State Estimate (SOSE; Mazloff et al., 2010) atlas and found bottom temperatures on the shelf adjacent to LCIS in line with those reported from hydrographic observations (-2 °C) but the bottom salinities were found to be far too fresh (34.5 psu). A fair comparison can therefore not be realistically made between NEMO and an atlas for the area adjacent to LCIS but by comparing the model output with the CTD results from Hutchinson et al. (2020; Fig. 3b) we find the "Closed" configuration to be too saline with bottom salinities (34.8 psu) greater than that observed. The overly saline conditions along the western flank of the Weddell Sea are likely a spill-over effect from the HSSW buildup seen in the Ronne Depression further south (Fig. 2f).

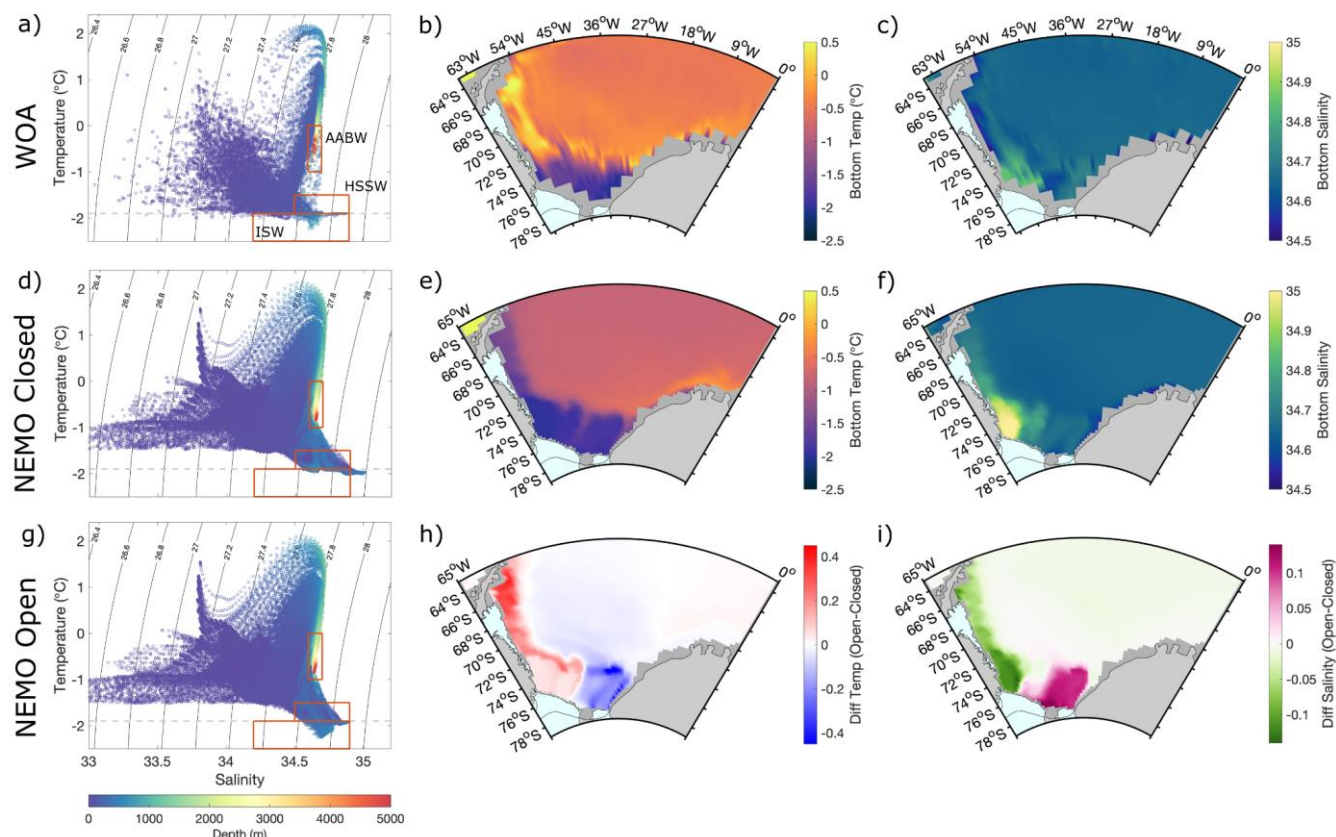
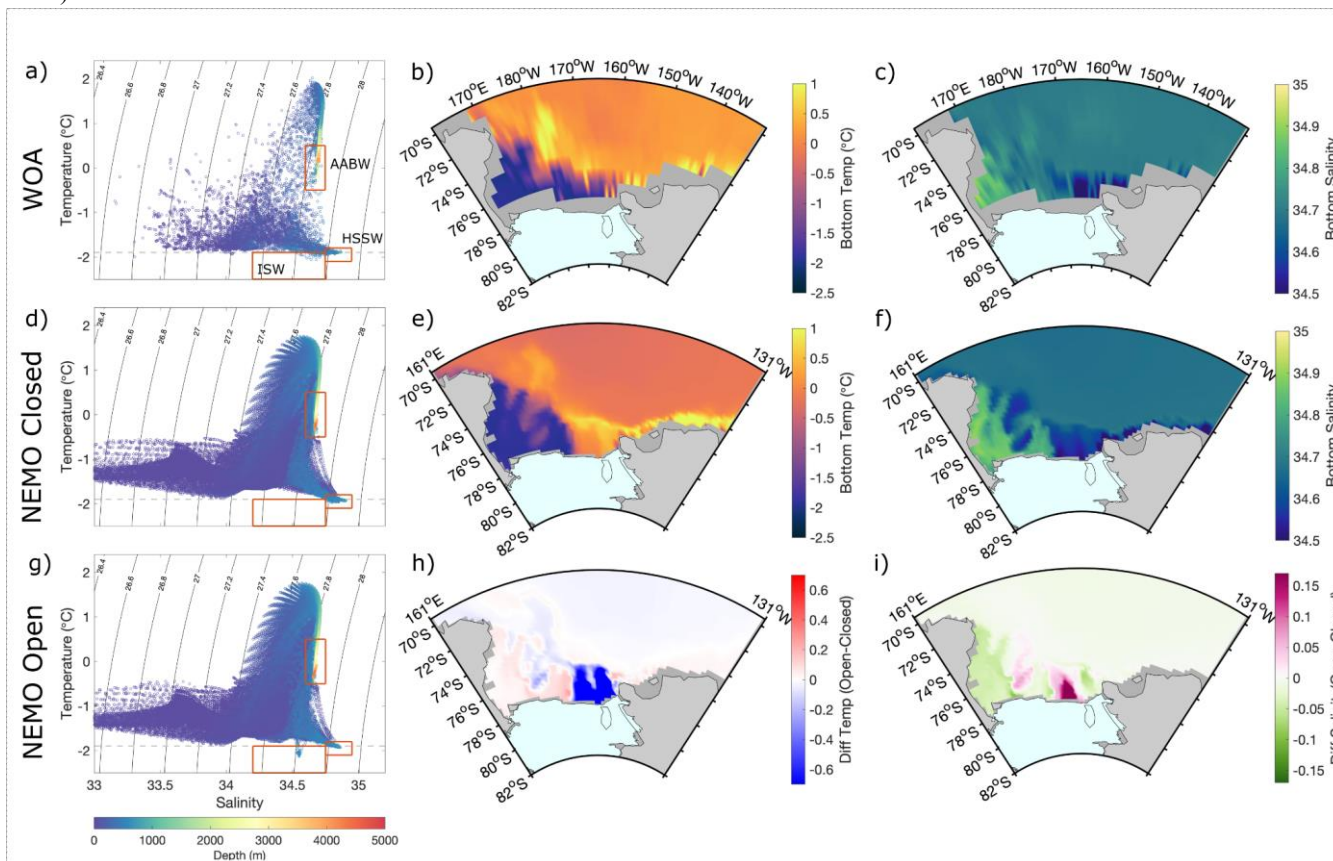



Figure 2: Weddell Sea comparison of NEMO v4.2 eORCA1 reference configuration ("Closed"; subplots d-f) for equivalent
years 1981-2009 to be compared with World Ocean Atlas (WOA; Locarnini et al., 2018; Zweng et al., 2018) observational
dataset (subplots a-c). The temperature salinity-distributions in density space are shown in plots (a), (d) and (g) with the
dashed gray line representing surface freezing point and labels in plot (a) indicating the observed ranges for properties
corresponding to Antarctic Bottom Water (AABW), High Salinity Shelf Water (HSSW) and Ice Shelf Water (ISW)
(Robertson et al., 2002; Hutchinson et al., 2020). Plots (b), (c), (e) and (f) show bottom temperature and salinity, and the
difference in bottom properties between the "Open" and "Closed" cavity configurations (Open - Closed) are shown in
subplots (h) and (i).

WOA bottom temperature and salinities for the Ross Sea indicate a strong east-west gradient in properties across the
continental shelf (Figs. 3b and 3c). Conditions in the south west reveal the cold and salty signature of HSSW likely formed
in the Terra Nova Bay polynya and the Ross Polynya. Intrusions of CDW at the eastern portion of the RIS front can be seen
by warm signatures of up to 1 °C (Figs. 3a and 3b) and fresher bottom salinities (Fig. 3c). Hydrological and current meter
data presented by Budillon et al. (2011) reported that HSSW dominates bottom properties within the troughs connected to
the Joides Basin, and ISW dominates in the Challenger Trough (see locations of bathymetric features in Fig. 1a) thus
indicating a western intensified anticlockwise circulation cell under RIS. In terms of HSSW properties, the model is within
the observed range (Fig. 3d) yet the proportion and salinity of HSSW in Terra Nova Bay and Joides Basin appears to be
overestimated (Fig. 3f). The bottom temperatures from NEMO indicate the presence of very warm waters, likely of

285 circumpolar origin right on the eastern continental shelf (Fig. 3e) whereas in observations this shelf is found to be cold and
286 the warm water confined offshore of the shelf break with only occasional intrusions (Bergamasco et al., 2003; Fig. 3b).
287 Again, there is no ISW in this standard configuration as there is no explicit model representation of ice shelf-ocean
288 interactions. Offshore bottom properties are slightly cooler than WOA in the model, but the AABW signature (AABW box
289 Fig. 3d) falls within the range reported from observations (Bergamasco et al., 2002; Bouillon et al., 2011; Silvano et al.,
290 2020).

291
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293 Figure 3: Same as Fig. 2 but for the Ross Sea.
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296 **4 Impact of explicit sub-ice shelf circulation**
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298 The following sections present results pertaining to the "Open" cavity run where the eORCA1 grid is extended under FRIS,
299 LCIS and RIS to allow for circulation within the cavities and explicit interaction with the base of these ice shelves.
300
301 **4.1 Melt rates**
302
303 The average melt rate pattern for FRIS, LCIS and RIS is shown in Fig. 4 for the model simulation equivalent years 1995 to
304 2009, where orange indicates melt and purple shows refreezing. The average net melt rate for this time period is shown in

305 Table 1 and compared to Depoorter et al. (2013) from which the volumes for the prescribed melt rates were taken for the
306 reference configuration ("Closed"). Opening the cavities results in at least double the melt reported from Depoorter et al.
307 (2013). This discrepancy reflects both a warm bias on the continental shelf in NEMO (Sect. 4.4) and a possible bias in
308 Depoorter's estimates which are lower than all other satellite estimates (Table 1). The net melt rates of each ice shelf from
309 various other observational and model studies are also listed in the table showing the wide spread in basal melt estimates
310 both within values calculated from observations and between observations and models (Table 1). The model studies of
311 Mathiot et al. (2017) and Bull et al. (2021), which are both regional NEMO 1/4° configurations, and the NEMO 1/12°
312 configuration of the southwestern Weddell Sea of Haussmann et al. (2020), are particularly relevant to compare eORCA1
313 with, as here we see the possible impact of lowering the resolution in NEMO. For the Weddell Sea, our global 1° (eORCA1)
314 compares well with these regional high resolution studies producing a net basal melt within 12 Gt/yr of the other estimates
315 for FRIS and LCIS. The eORCA1 melt rate for RIS, while being higher than observational studies, is in the middle of other
316 model estimates, and is especially well aligned with that of NEMO 1/4° from Mathiot et al. (2017). Overall, eORCA1's net
317 melt rates correspond well with the average from all other estimates and are well within the standard deviations (last line of
318 Table 1).
319

Values in Gt/yr	FRIS	LCIS	RIS
NEMO 4.2 eORCA1 (1995-2009)	117 ± 21	36 ± 7	112 ± 22
Obs			
Depoorter et al., 2013 (1995-2009)	50 ± 40	18 ± 8	34 ± 25
Adusumilli et al., 2020 (1994-2018)	81 ± 123	78 ± 99	80 ± 82
Rignot et al., 2013 (2003-2008)	155 ± 36	21 ± 67	48 ± 24
Moholdt et al., 2014 (2003-2009)	124		50
Models			
Mathiot et al., 2017 (1988)	123	46	111
Timmermann et al., 2012(1980-1999)	138	48	260
Hellmer et al., 2004 (1978-1997)	119	38	180
Naughten et al., 2018 (FESOM HR) (2002-2016)	115	55	112
Naughten et al., 2018 (MetROMS) (2002-2016)	46	18	54
Haussmann et al., 2020 (1993-1997)	105	24	
Bull et al., 2021 (1986-2017)	124		
Average from all the above excluding present study	111 ± 33	37 ± 21	118 ± 87

320
321 Table 1: Comparison of mean net melt rates (Gigatons per year) for Filchner-Ronne (FRIS), Larsen C (LCIS) and Ross Ice
322 Shelves (RIS) for observational and model studies. The mean and standard deviation of all the estimates depicted in the table
323 excluding the current study are shown at the bottom.
324
325 The patterns of melt shown in Fig. 4 also compare well with those of observational estimates like Rignot et al. (2013) and
326 high resolution model results like Haussmann et al. (2020) whose color bar we replicated for ease of cross-comparison. If we
327 look at the melt pattern of FRIS and compare it with these two aforementioned studies, we see that eORCA1 captures the

328 high melt rates at the western portion of the ice shelf front, at the southern edge of Berkner Island and along the grounding
329 line at the back of the cavity. The model also correctly simulates the region of refreezing along the western boundary of the
330 circulation cell within the cavity, in both the Ronne and Filchner depressions and the re-freezing in the shallow region
331 between the Korff and Henry Ice Rises (Fig. 4a, see bathymetry location in Fig. 1b). For LCIS, the entire shelf shows a
332 positive melt (Fig. 4b). Observations from Rignot et al. (2013) and simulations from Harrison et al. (2022) indicate some re-
333 freezing under this ice shelf but the regional high resolution model studies of Mathiot et al. (2017) and Haussmann et al.
334 (2020) similarly show melting only. The pattern for RIS generally compares well with that reported from observations but
335 the magnitude of melt at the ice shelf front, especially to the east, is elevated (Fig. 4c).

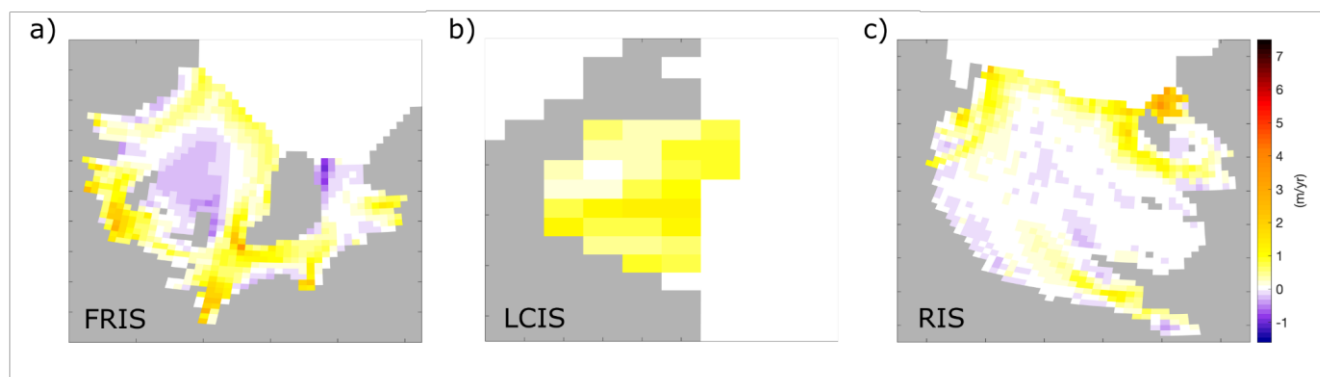



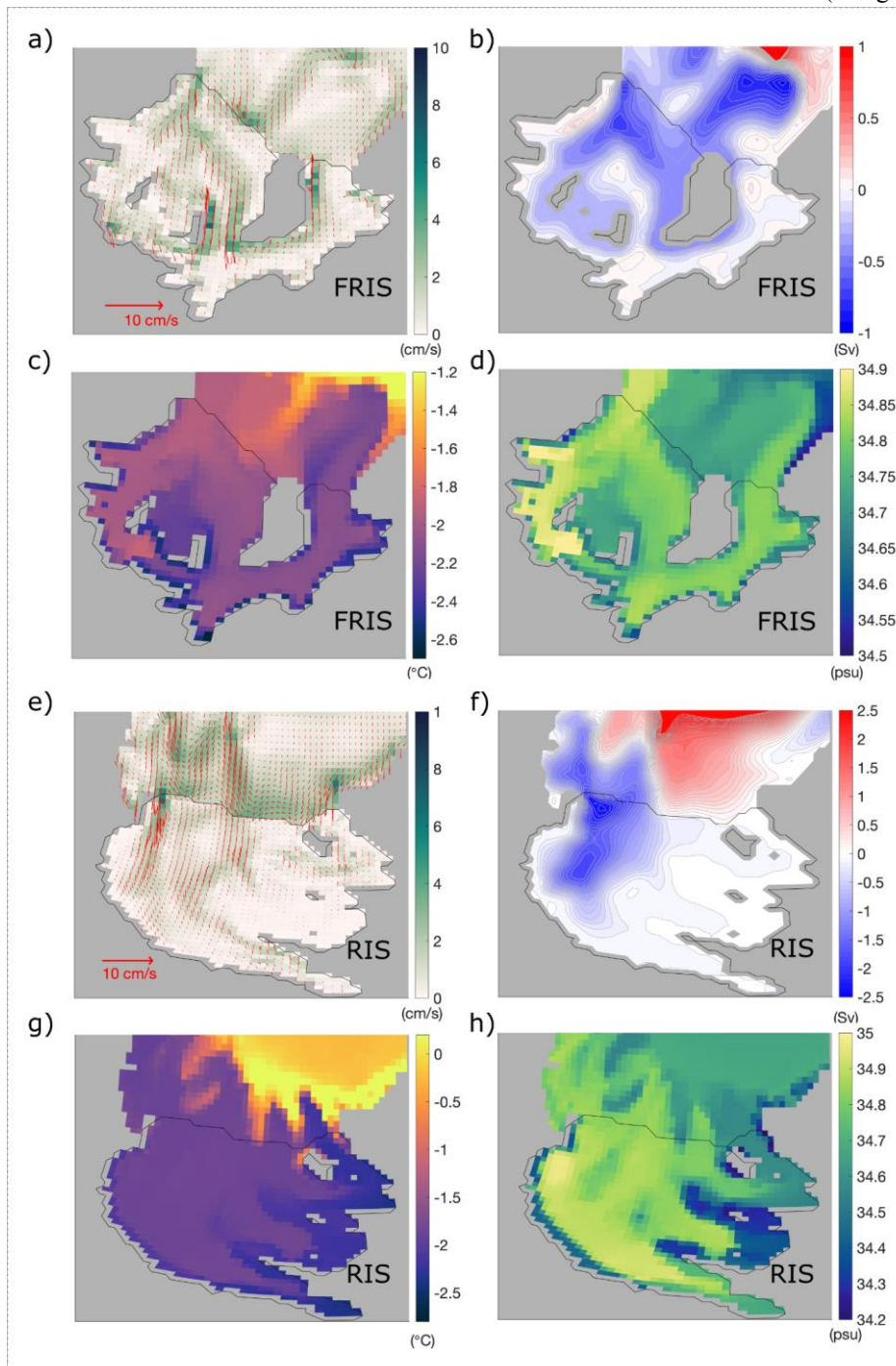
Figure 4: Melt rates in meters per year for (a) Filchner-Ronne Ice Shelf, (b) Larsen C Ice Shelf and (c) Ross Ice Shelf where
orange indicates melt and purple re-freezing. The results are mean values for the model equivalent period 1995-2009.

4.2 Circulation and properties

Opening the sub-ice shelf cavities in eORCA1, allows for the establishment of a horizontal gyre circulation within the cavity
and on the continental shelf of the Weddell and Ross Seas, in line with previous studies (Losch et al., 2008; Mathiot et al.,
2017).

4.2.1 FRIS

350 The mean state of circulation from the last 10 years of simulation within the FRIS cavity, along with the associated bottom
351 thermohaline properties can be seen in Figs. 5a-5d. The circulation patterns shown here are in good agreement with Bull et
352 al. (2021) at 1/4° and with Hausmann et al. (2019) at 1/12° with the exception of higher bottom salinities in eORCA1 and a
353 slightly weaker barotropic circulation strength. Note that here we use potential temperature and practical salinity so as to be
354 in line with the other figures of this paper, so approximately 0.17 psu must be added when juxtaposing with absolute salinity
355 plots. The depth averaged velocity and barotropic circulation pattern in Figs. 5a and 5b both indicate an anticlockwise
356 circulation under the ice shelf. Comparatively warm and salty HSSW enters via the Ronne Depression, circulates from west
357 to east, melting the base of the ice shelf mostly along the grounding line (cold, fresh signatures in Figs. 5c and 5d), and exits
358 via the Filchner Trough as ISW. This pattern is consistent with observations (Nicholls et al., 2001; Janout et al., 2021). Two
359 pathways of Modified Warm Deep Water (MWDW) towards the ice shelf front can be seen, both in the circulation pattern
360 (Fig. 5a) and via the bottom temperature (Fig. 5c): one located in the middle of the continental shelf (Central Trough) and
361 the other on the shelf to the east of Filchner Trough. These pathways provide a conduit for heat towards the ice shelf and

362 facilitate the mixing of shelf water masses with MWDW. It is therefore encouraging that eORCA1 captures these as they
363 could play an important role in the evolution of FRIS shelf circulation in future climate scenarios (Naughten et al., 2021).

364
365 Figure 5: Circulation pattern and characteristics of properties under Filchner Ronne (a-d) and Ross (e-h) ice shelves for the
366 last 10 years of the open cavity experiment. Subplots (a) and (e) show depth averaged velocity, (b) and (f) barotropic stream

367 function, (c) and (g) bottom potential temperature and (d) and (h) bottom practical salinity (as opposed to conservative and
368 absolute shown in Bull et al., 2021).

4.2.2 RIS

372 Moving now to the Ross Sea, the time mean circulation pattern under RIS along with the bottom temperature and salinity
373 can be seen in Figs. 5e-5h. Here we notice a strong anticlockwise circulation concentrated at the western boundary with
374 reduced magnitude currents towards the back and east of the cavity. The west of the cavity is overall warmer and saltier and
375 the east shows signatures of ISW. Bottom temperature indicates the presence of a cold ISW plume exiting the cavity to the
376 far east (Fig. 5g) which is not seen in the time averaged velocities or barotropic streamfunction, likely because the associated
377 speeds are extremely slow. Instead, the simulated circulation indicates an offshore advection of sub-ice shelf water following
378 the Challenger Trough (see location marked in Fig. 1a). This water mass is likely recirculated HSSW as its temperature
379 remains at surface freezing point (-1.9 °C). A strong clockwise circulation cell offshore of RIS (red in Fig. 5f) brings warm
380 CDW into contact with the ice shelf front to the east, mixing out the signature of ISW further offshore (Fig. 5g). While this
381 simulated circulation pattern agrees well with that described by observations (Fig. 1; Bergamasco et al., 2003; Budillon et
382 al., 2003), it is likely too strong, resulting in an exaggerated net melt rate compared to the observational estimates (Table 1;
383 anomalously high melt at the eastern portion of the ice shelf front in Fig. 4c).

4.3 Impact on offshore properties

388 To highlight the impact of opening the FRIS, LCIS and RIS sub-ice shelf cavities on the offshore properties, Figs. 2g and 3g
389 show the temperature versus salinity distribution excluding the data under the ice shelves. The differences in bottom
390 temperature and salinity can be seen in Figs. 2h and 2i for the Weddell Sea and 3h and 3i for the Ross Sea.

392 A significant improvement in the representation of Weddell shelf water properties is evident as now HSSW is within the
393 observed range and ISW is detected on the continental shelf (see HSSW and ISW red boxes in Fig. 2g). Opening the sub-ice-
394 shelf cavity of FRIS has allowed the HSSW that previously built up in the Ronne Depression to advect under the ice shelf,
395 become modified through basal interactions and exit the cavity as colder and fresher ISW. Consequently, the temperature
396 and salinity differences are polarized west and east with warmer fresher conditions along the entire western boundary of the
397 Weddell Gyre and cooler saltier conditions on the eastern continental shelf (Figs. 2h and 2i). These results agree well with
398 those of Mathiot et al. (2017). The impact of opening LCIS can be seen via the maintenance of cold bottom properties
399 immediately to the north (despite the fact that the shelf circulation has changed so that HSSW no-longer floods this region),
400 along with the presence of a large negative salinity anomaly indicative of ice shelf melt (Fig. 2i). As the simulation is only
401 124 years long, the impact of opening the cavities on AABW cannot be fully assessed due to the slow renewal of this water
402 mass at the bottom of the global ocean. A small change in signature of AABW can, however, be seen in the volumetric T-S
403 plot (supplementary material Fig. S1a) where explicit ocean-ice shelf interaction results in a shift in volume towards fresher,
404 slightly cooler AABW. This shift is accompanied by a small increase in volume of the water mass by 0.23 % (AABW limits
405 delineated in green in Fig. S1a).

407 The impact of opening the RIS cavity on offshore properties can be seen in Figs. 3h and 3i. Similar to the Weddell Sea,
408 conditions in the west where in the reference run HSSW was built up, now become warmer and fresher as the path under the
409 ice shelf is open. The signature of the cold plumes of dense shelf water (Fig. 5g) on either side of Roosevelt Island can
410 clearly be seen in the temperature difference plot (Fig. 3h), but curiously they do not possess the same salinity anomaly (Fig.

Figure 6: Validation of properties across the Filchner Ronne Ice Shelf front by comparing closed and open cavity NEMO results with measured values from CTD sections performed in 1980 (Rohardt et al., 2016) and 1995 (Janout et al., 2021). The model output for the corresponding equivalent year and month was extracted for more accurate comparison. Bathymetric features discussed in the text are labelled in subplot (a).

The CTD sections used for comparison along the front of RIS were obtained through the World Ocean Circulation Experiment Database (Boyer et al., 2018) and correspond to cruises undertaken on board the RVIB Nathaniel B. Palmer in 2000 (cruise id: US010404; Smethie and Jacobs, 2005) and in 2007 (cruise id: US034357). Data was extracted from the eORCA1 simulation corresponding to the dates of these cruises and the approximate ship track across the ice shelf front (magenta dotted line in Fig. 1a). Similar to the Weddell Sea, the model tends to overestimate the subsurface temperature and salinity (Figs. 7b, 7e, 7h and 7k), suggestive of biases in the representation of coastal processes, including vertical mixing. This effect is somewhat reduced by allowing for circulation under RIS, especially by decreasing subsurface salinities (Figues

465 7f and 7l). At depth, NEMO captures the east-west distribution of haline properties such as the HSSW pool located within
466 Joides Basin, albeit with somewhat amplified salinities. In terms of temperature, the model has a clear bias to the east,
467 especially in the closed cavity run, where CDW is detected at the ice shelf front. Both the temperature and salinity biases are
468 reduced in the open cavity run (e.g. Figs. 7c and 7f). In particular, the significant reduction in the extent and magnitude of
469 the sub-surface warm water intrusions brings the model more in-line with observations.

470

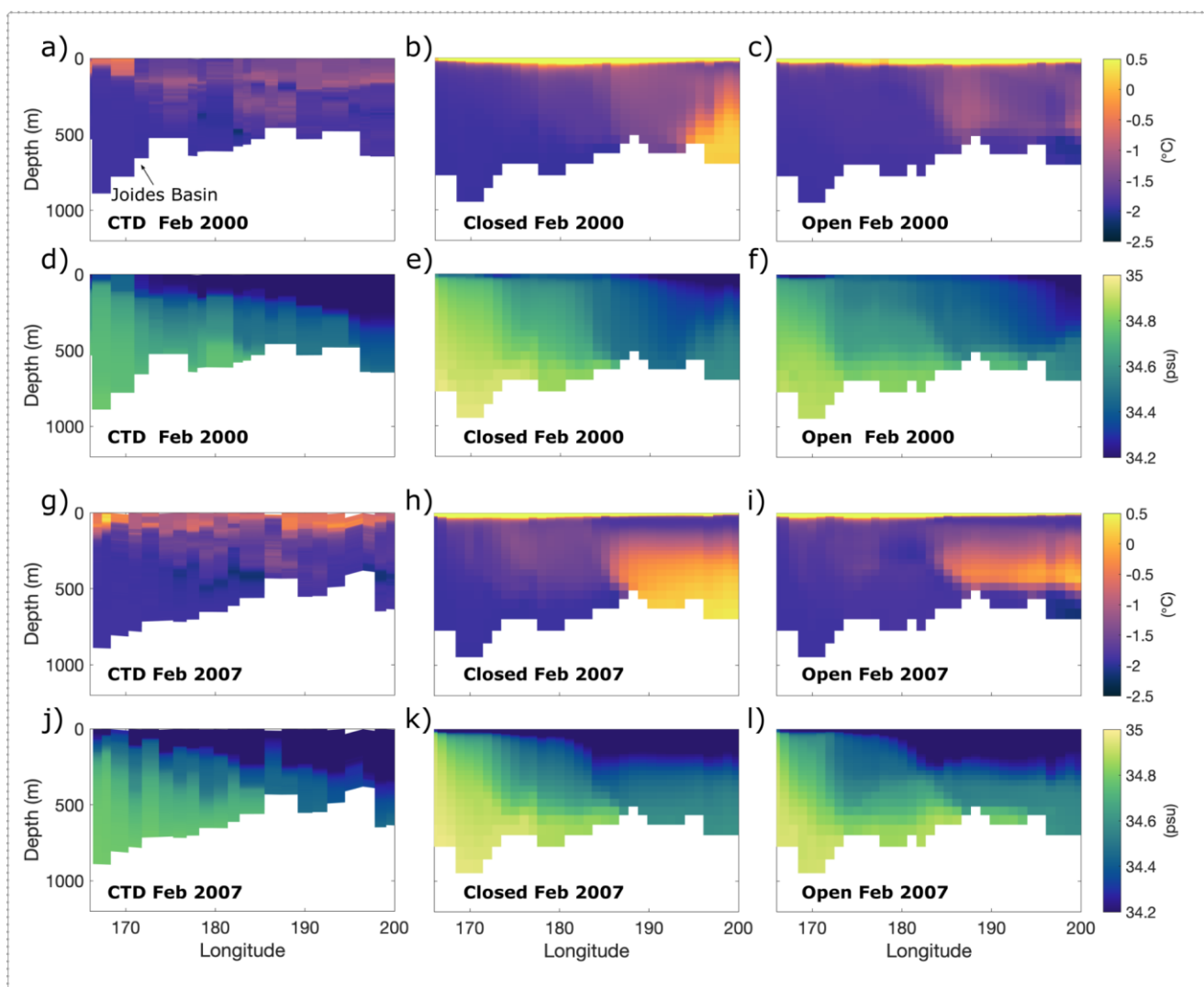



Figure 7: Same as Fig. 7 but for Ross Ice Shelf front for CTD sections performed in 2000 (Smethie and Jacobs, 2005) and
2007 (Boyer et al., 2018).

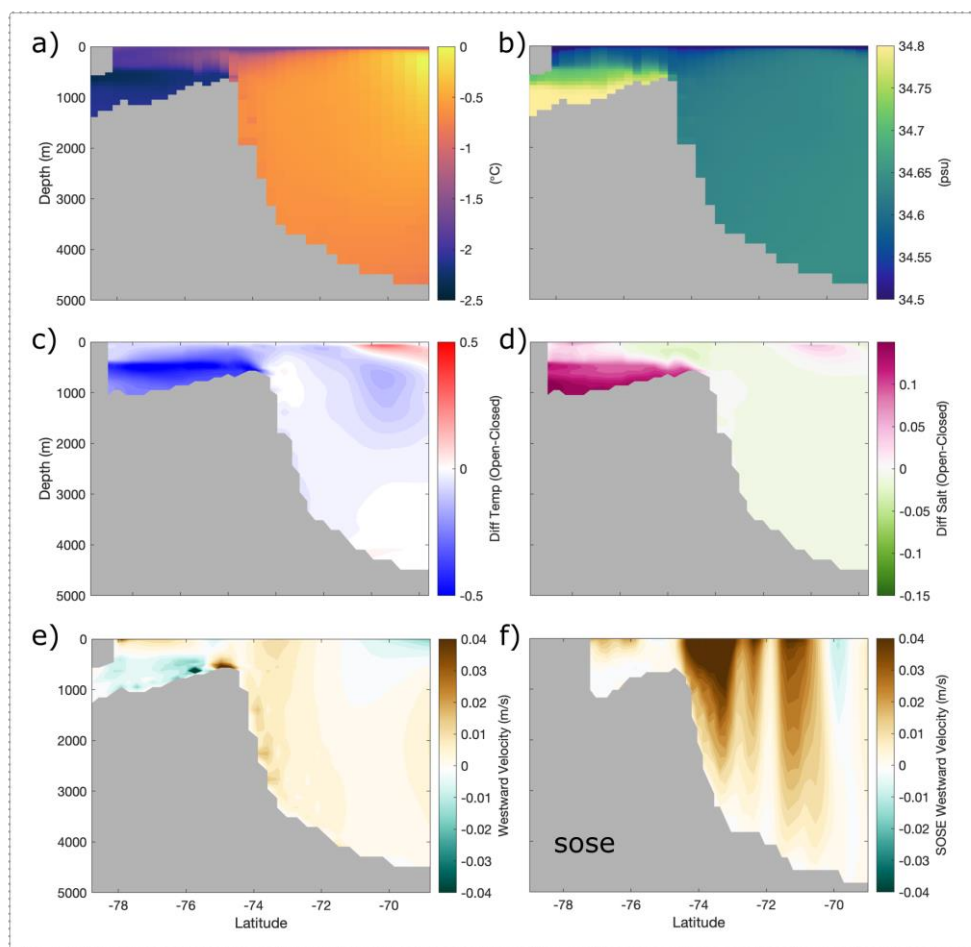
476 A recurring theme throughout the results presented here is that the model is overall too salty, driven by what appears to be an
477 over-production of HSSW in the Ronne Depression and Joides Basin. One driver for this could be the hyper-activity of dense
478 water formation via open-ocean convection which forms the totality of parent waters of AABW in the absence of ice shelves

479 in eORCA1. This can be seen in Supplementary Material Fig. S2 where the mean winter (July-August-September) mixed
480 layer depths (MLD) in the reference run for the years 1971-2009 (Fig. S2c and S2d) are compared to the climatology from
481 Sallee et al. (2021) for the same time period and using the same criteria for calculation (Fig. S2a and S2b; MLD defined as
482 the depth at which density exceeds the 10 m density by 0.03 kg m^{-3}). The model greatly overestimates winter MLDs in the
483 Weddell Sea, both on the continental shelf adjacent to FRIS where the depth of the base of the mixed layer aligns with
484 bathymetric features indicating deep convection right to the ocean floor, and offshore of the continental slope where a large
485 region of MLD greater than 1000m is present (Fig. S2c). This level of open ocean deep convection has in reality only once
486 been observed, during the 1974-1976 Weddell Polynya, indicating a gross overestimation of winter MLDs in the model
487 (Heuze et al., 2021; Killworth et al., 1983). Ross Sea MLDs (Fig. S2d) compare better with observations, but show values
488 indicating a full water-column-depth convection in Terra Nova Bay which is not reported in Sallee at al. (2021). Curiously,
489 NEMO actually under-estimates winter mixed layers in the eastern portion of the Ross continental shelf showing mean
490 MLDs of under 100m where the observational climatology indicates values of around 400m (Fig. S2d compared to Fig.
491 S2b). This too-strong stratification could be one of the factors facilitating the intrusion of CDW to the ice shelf front seen in
492 Figs. 7b and 7h.
493
494 Note that if ISW is explicitly formed, as in the open cavity experiment, the exaggerated deep convection on the shelf should
495 be reduced, otherwise the signatures of ISW and modified HSSW will simply be mixed out. Some reduction in MLD is seen
496 on the continental shelf and slope in the Filchner (Fig. S2e) and Challenger Troughs (Fig. S2f) due to the increase in
497 stratification as a result of the greater bottom densities present in these areas (Fig. S5a and S5c) and surface freshening (Figs.
498 8d and 9d). Conversely, the regions of exaggerated MLDs, offshore in the center of the gyre of the Weddell Sea, and in Terra
499 Nova Bay in the Ross Sea actually deepen (positive anomalies Figs. S2e and S2f). This highlights the need for work to be
500 done on reducing wintertime deep convection and would complement efforts underway on better representing dense water
501 overflows.
502
503 The authors note that the biassed MLDs could be one of a number of factors driving the overly saline conditions; wrong sea-
504 ice parameters and biases in the atmospheric forcing could also play an important role. High ice production is seen on the
505 southwest continental shelves of the Weddell and Ross Seas in Supplementary Figs. S3c and S4c. Opening the cavities
506 reduces the magnitude of ice production in the Ronne Depression (Fig. S3d) and at the location of the Terra Nova Bay
507 Polynya (Fig. S4d) but increases the production of ice (and thus HSSW) further east. The result is a re-organisation of the
508 locations of HSSW formation and a redistribution of the continental shelf circulation. This does not fully correct for the net
509 over production of HSSW and thus the positive salt bias seen in Figs. 6 and 7, but it does work towards decreasing bottom
510 salinities offshore (Figs. 2i and 3i) and bringing the HSSW signature more in line with observations (Figs. 2g and 3g). Please
511 see the Supplementary Information for an in-depth evaluation of simulated sea ice near the studied ice shelves and a
512 diagnosis on the effect of opening the cavities on sea ice.
513
514 **4.5 Offshore export of continental shelf properties**
515
516 We have seen how opening the large, cold, ice shelf cavities in eORCA1 leads to a better representation of continental shelf
517 circulation and thermohaline property distributions. But the question remains regarding the transfer of these now more
518 realistic dense shelf waters, offshore, to feed the globally important AABW. While the simulation period of 124 years (2
519 CORE forcing cycles) is too-short to explore the impact of these changes far-afield, it is sufficient to investigate the changes
520 on the continental shelf and slope adjacent to the large ice shelves. To do this, we use PAGO (Deshayes et al., 2014) to select
521 a cross section of data following the bathymetric troughs of the Weddell and Ross Seas which are thought to be important for
522 dense water export, namely the Filchner and Challenger Troughs (sections shown in green in Fig. 1).

523

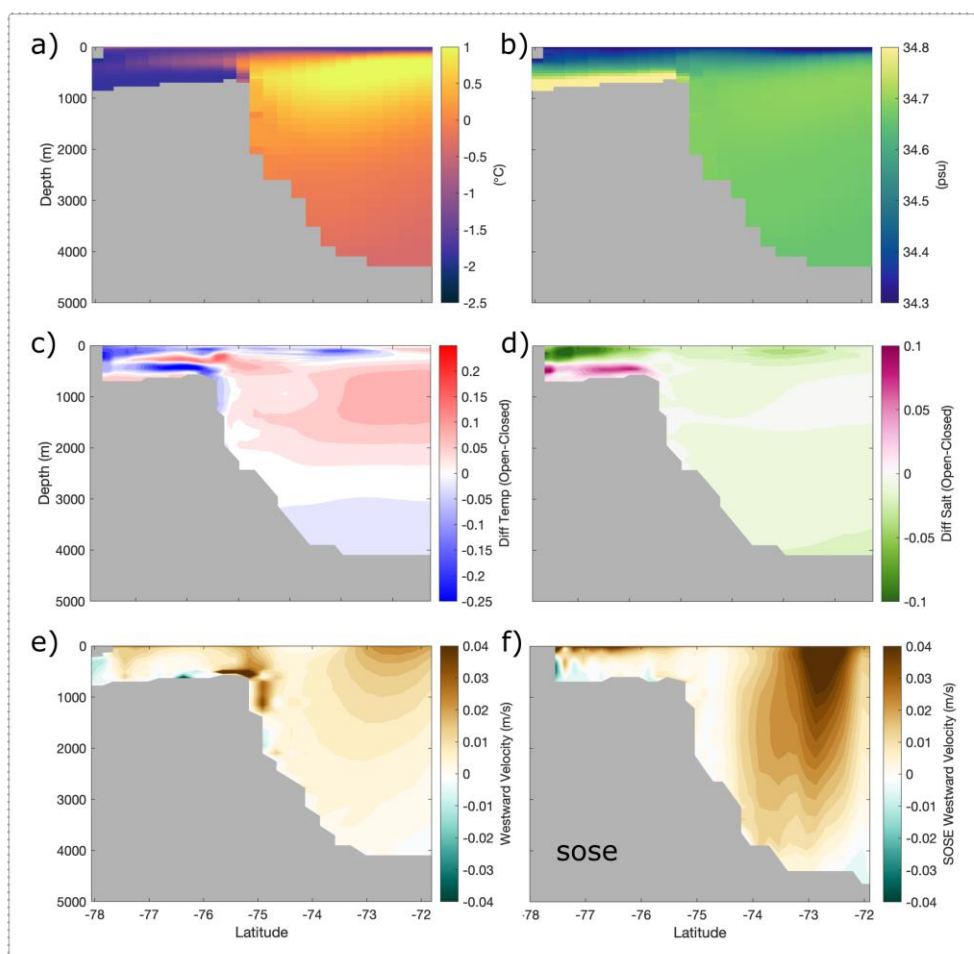
524 The thermohaline and velocity cross sections of Filchner Trough and a continuation down the continental slope can be seen
525 in Figs. 8a and 8b for the open cavity run and the difference between these values and the reference run (Open-Closed) are
526 shown in Figs. 8c and 8d. By opening the sub-ice shelf cavity, the properties within Filchner Trough have decreased in
527 temperature and increased in salinity as the candidate-parent waters of AABW build up on the continental shelf. This results
528 in a net increase in density at the bottom of the trough (Fig. S5b), but there is very little indication of a coherent cascading of
529 this water down the continental slope.

530

531

532 Figure 8: Cross section of properties along the Filchner Trough and down the adjacent continental slope of the Weddell Sea
533 for (a)-(e) NEMO and (f) SOSE. Subplots (a) and (b) show temperature and salinity for the open cavity configuration, to be
534 compared to (c) and (d) which show the differences (Open - Closed) with the reference configuration. Subplot (e) shows
535 cross sectional velocities with westward as positive for the open cavity run, to be compared with SOSE values shown in
536 subplot (f).

537

538 A cross section of the Challenger Trough (Fig. 9), reveals depth-varying thermohaline changes as opening the sub-ice shelf
539 cavity has allowed for the water adjacent to the ice shelf to advect into the cavity leaving the bottom properties here slightly

540   warmer, while the layer immediately above experiences cooling and salinification due to the outflow of ISW driven by the
541   'ice pump' (Fig. 9c). Here we see some evidence indicating the translation of this dense cold water tongue over the
542   continental shelf break and downslope (Figs. 9c and S5d). The overflow of this water results in the pulling in of warmer
543   offshore water at intermediate depth (Fig. 9c). A horizontal redistribution of surface waters simultaneously takes place due
544   to the anti-clockwise circulation pattern (Fig. 5e) which in turn produces a cooling and freshening in the surface layer (Figs.
545   9c and 9d).
546

547
548   Figure 9: Same as Fig. 9 but for the Challenger Trough and the Ross Sea continental slope.
549
550   For both the Filchner and Challenger Troughs, the downslope export of the ISW tongue is limited due to the commonly-
551   known and acknowledged problem of correctly capturing this overflow in a coarse z-coordinate model (Heuze et al., 2021).
552   The aptitude of representing dense water overflows is thought to increase with models of higher resolution, but this is
553   difficult to achieve in a global model for climate coupling purposes without a nested zoom (Storkey et al., 2018; Solodoch et
554   al., 2022).
555

556 Another important dynamic for Antarctic shelf water realism is the Antarctic Slope Current (ASC; red arrows in Fig. 1) and
557 related Antarctic Slope Front, which together restrict the lateral mixing of offshore and shelf water masses, acting as an
558 effective barrier protecting the large cold ice shelves from warm water masses of circumpolar origin (Thompson et al.,
559 2018). Some CDW, or a modified version thereof, is carried within the ASC and occasionally fluxes onshore to mix with
560 dense shelf waters (Beadling et al., 2020; Bull et al., 2021). This interaction between dense shelf water and CDW is
561 important for the formation of AABW, as the onshore flux of water replaces the dense water transported offshore and thus
562 sustains formation of shelf water (Thompson et al., 2018). Figure 8e shows a velocity cross section for the Weddell Sea shelf
563 and slope where westward velocities are positive so as to correspond with the direction of the ASC and the net westward
564 transport across the section is 9.8Sv. This can be compared to Fig. 8f which is a cross section from SOSE output (same time
565 periods used) where the net transport is three times higher at 32.8Sv. Similarly for the Ross Sea, Fig. 9e shows a cross
566 section of westward velocities in eORCA1 where the volume transport is 13.3Sv which is less than half of that estimated
567 from SOSE in Fig. 9f of 20.9Sv. As can be seen from both SOSE cross sections, the ASC flows eastward as a narrow jet,
568 closely following the shelf break in the Weddell Sea and slightly further offshore in the Ross Sea. It is well known that
569 coarse resolution models are unable to correctly represent the ASC as a resolution of at least 0.5° is needed to capture the
570 dynamics and net transport (Mathiot et al., 2011). The absence of realistic ASC in NEMO eORCA1 (Figs. 8e and 9e) has
571 important consequences for the onshore-offshore exchange of water masses and is a restriction that needs to be kept in mind
572 when using this coarse resolution configuration for process studies in the area.
573
574
575 **5 Discussion**
576
577 Explicitly representing ocean-ice shelf interactions is of great interest to modelers as these processes play an important role
578 in global ocean dynamics, climate and future sea level rise. The formation of dense shelf waters (HSSW and ISW) along the
579 Antarctic coastline provides the principal source for AABW, which in turn facilitates the ventilation of the deep ocean and
580 constitutes the lower limb of the global overturning circulation (Killworth, 1983; Johnson, 2008; Orsi, 2010).
581
582 Our results focus on the Weddell and Ross seas as they are respectively the main ventilation source of the abyssal Atlantic
583 and Indian basins, and the abyssal Pacific basin (Solodoch et al., 2022). Explicitly simulating the sub-ice shelf cavities of
584 FRIS and LCIS in the Weddell Sea leads to a re-organisation of continental shelf circulation with thermohaline patterns in
585 agreement with those reported by other NEMO model studies (Mathiot et al., 2017; Storkey et al., 2018 and Bull et al.,
586 2021), namely warming and freshening in the west and cooling and salinification in the east. Notably, opening a pathway for
587 HSSW under FRIS allows for an anticlockwise circulation of water under the ice shelf, triggering basal melt and re-freezing,
588 and producing the super-cold ISW. In both the Weddell and Ross Seas, opening the cavities decreases sea ice production to
589 the west of the ice shelves, assisting in the partial reduction of the salt bias in these areas linked to polynya activity.
590
591 By comparing model output with two CTD sections performed across the front of FRIS in 1980 and 1995 (Rohardt et al.,
592 2016; Janout et al., 2021), we see clear evidence of an improvement in the realism of water properties with the opening of
593 the sub-ice shelf cavity. Similarly in the Ross Sea, an anticlockwise sub-ice shelf cavity circulation cell facilitates the spread
594 of HSSW across the continental shelf and ocean-ice shelf interactions create a cold ISW plume to the east of Roosevelt
595 Island. By evaluating the model output against CTD sections performed in 2000 and 2007 (Smethie and Jacobs, 2005; Boyer
596 et al., 2018), we see that opening the cavity significantly ameliorates the sub-surface warm water bias otherwise seen to the
597 east of RIS in the reference configuration, and brings a significant improvement in the horizontal thermohaline distributions.
598

599 The net melt rates of FRIS, LCIS and RIS are found to be within the uncertainty range of observational estimates and other
600 model studies. Notably, the melt rate pattern of FRIS agrees surprisingly well with the high resolution regional model of
601 Haussmann et al. (2020) and the satellite observations of Rignot et al. (2013), showing details of melt and refreezing that
602 were not expected at a 1° resolution, although the meanders of the grounding line are not well represented at 1°. For RIS, the
603 net melt is higher than all observed estimates but lower than that predicted by other model studies. RIS melt rates are
604 strongly related to the supply of warm water to the ice shelf base (Arzeno et al., 2014), and correctly representing this in
605 models presents a challenge due to the close proximity of CDW to the ice shelf front in this area.

607 Meltwater and modified HSSW mix on the continental shelves of the Weddell and Ross Sea and in reality cascade down the
608 continental slope, mixing with ambient water masses during the descent, to eventually feed AABW. This process is poorly
609 represented in NEMO eORCA1, a common problem with coarse z-coordinate models, as exaggerated vertical and horizontal
610 mixing erodes the signatures of the dense overflow tongue. As mentioned by Storkey et al. (2018), the use of a terrain
611 following coordinate system (known as sigma coordinate) can greatly improve the representation of these density currents,
612 and so is something worth exploring in the future. Improvement in the representation of the overflows along with a reduction
613 of open-ocean deep convection should together allow for a coherent communication of the now more realistic properties of
614 dense water on the continental shelf offshore to AABW.

616 **6 Conclusion**

618 In this paper the authors focus on improving the properties of AABW parent waters in a global NEMO configuration. We
619 compare the model simulations with local in situ observations, in addition to gridded climatologies, so as to deepen
620 understanding and expertise regarding the impact of opening sub-ice shelf cavities on ocean dynamics. As ocean models
621 used for climate simulations with multiple scenarios (such as CMIP) need to be at a coarse resolution to permit long
622 integrations, we use the NEMO global ocean 1° configuration, eORCA1, here. The results presented are for CORE inter-
623 annual forcing, with a fixed cavity geometry, as this allows us to clearly identify the impact of ocean-ice shelf interactions at
624 a few critical locations without the obscuring effect of coupling feedbacks. We present here a validated configuration of
625 NEMO 4.2 eORCA1 with explicit ocean-ice shelf interactions only within the largest 3 cold-core cavities: FRIS, LCIS and
626 RIS. Limitations of this choice are that together FRIS, LCIS and RIS only represent 63 % of the total area of Antarctic ice
627 shelves and while they are responsible for the formation of the majority of the parent waters of AABW, interactions with
628 remote unresolved ice shelves is missing (Nakayama et al., 2020). The next steps in terms of increasing complexity in
629 NEMO eORCA1 are to open other intermediate size cavities, such as Amery, Riiser-Larsen and Fimbul, in a fixed geometry
630 configuration. As the residence time needed to flush these smaller cavities is shorter than for FRIS and RIS, we suggest that
631 the complex initialization methods presented here are not needed. This work is aimed at building understanding so as to
632 eventually move to coupling with an ice sheet model thereby allowing for fully evolving cavity geometry and iceberg
633 calving from the ice shelf front.

635 Given the critical role that the Southern Ocean plays in regulating global climate, it is paramount that ocean models work
636 towards improving the representation of key processes in order to provide state-of-the-art simulations of the ocean in a
637 changing climate (Beadling et al., 2020). The global configuration of NEMO presented here, has been proven to improve the
638 realism of water masses in the Weddell and Ross Seas. We advocate for climate modelers to use it, as it enables a more
639 accurate representation of the formation of the parent waters of AABW, and a first step in the perspective of representing
640 ocean-ice shelf interactions in climate applications.

7 Author contribution

KH, JD and PM together contributed to the conceptualization of the research outlined in this manuscript. KH led the formal analysis and investigation with the assistance of JD, CR, CL, NJ and PM. MV led the sea ice research component with assistance from CL. Validation of the model was undertaken by KH with PM. CE led the programming, code management and supervised all the model runs undertaken by KH. The project was supervised by JD and NJ, providing guidance and critical feedback. The whole group contributed to the writing and review of the submitted manuscript.

8 Competing interests

The authors declare that they have no conflict of interest.

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10 Code and data availability

The NEMO ocean model code is available via open software license from the NEMO website (https://www.nemo-ocean.eu). The NEMO output for the Weddell and Ross Seas (focus of this study), plus the namelists used, bathymetry, ice shelf draft, freshwater input and initial condition files are available via the data repository stored here: https://doi.org/10.5281/zenodo.7561767. Some example scripts for data extraction, calculations and plotting can also be found in this repository. The World Ocean Atlas hydrographic data of Locarnini et al. (2019) and Zweng et al. (2018) can be found here: https://www.nodc.noaa.gov/OC5/woa18/woa18data.html and Southern Ocean State Estimate data of Mazloff et al. (2010) can be accessed here: http://sose.ucsd.edu/sose_stateestimation_data_05to10.html. The mixed layer depth data from Sallee et al. (2021) can be accessed here: https://doi.org/10.5281/zenodo.5776180. The CTD transects used for comparisons across the ice shelf front for FRIS 1980 and 1995 can be respectively found here: https://doi.org/10.1594/PANGAEA.860066 and here https://folk.uib.no/ngfso/Data/CTD/. The RIS CTD data from the 2000 (US010402) and 2007 (US034357) RVIB Nathaniel B. Palmer cruises are available from the World Ocean Data Base at https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html. The PAGO toolbox used to extract model output along a line in front of the ice shelf from Deshayes et al. (2014) can be accessed here: https://www.whoi.edu/science/PO/pago/.

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