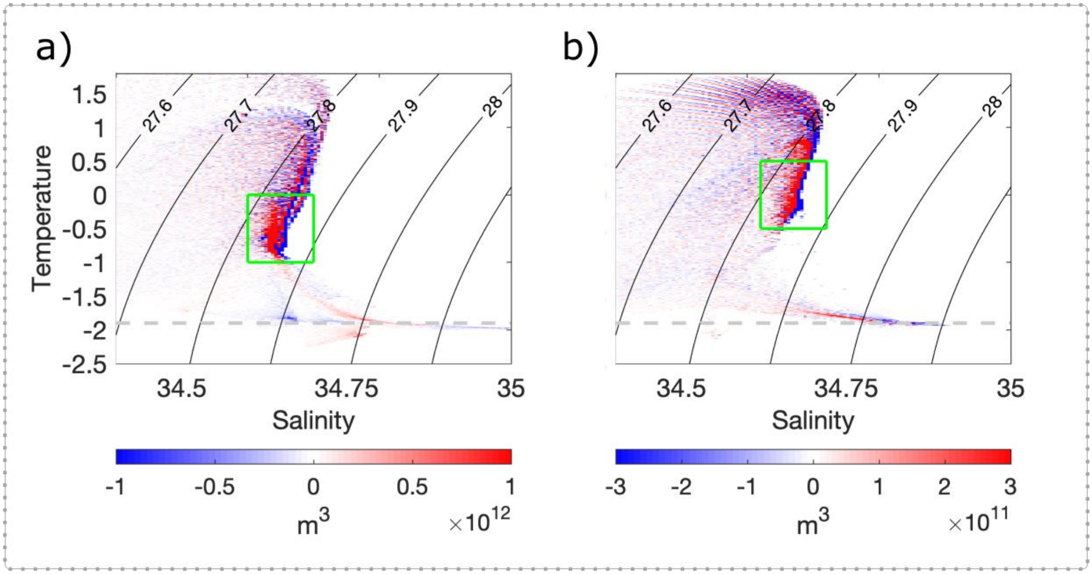
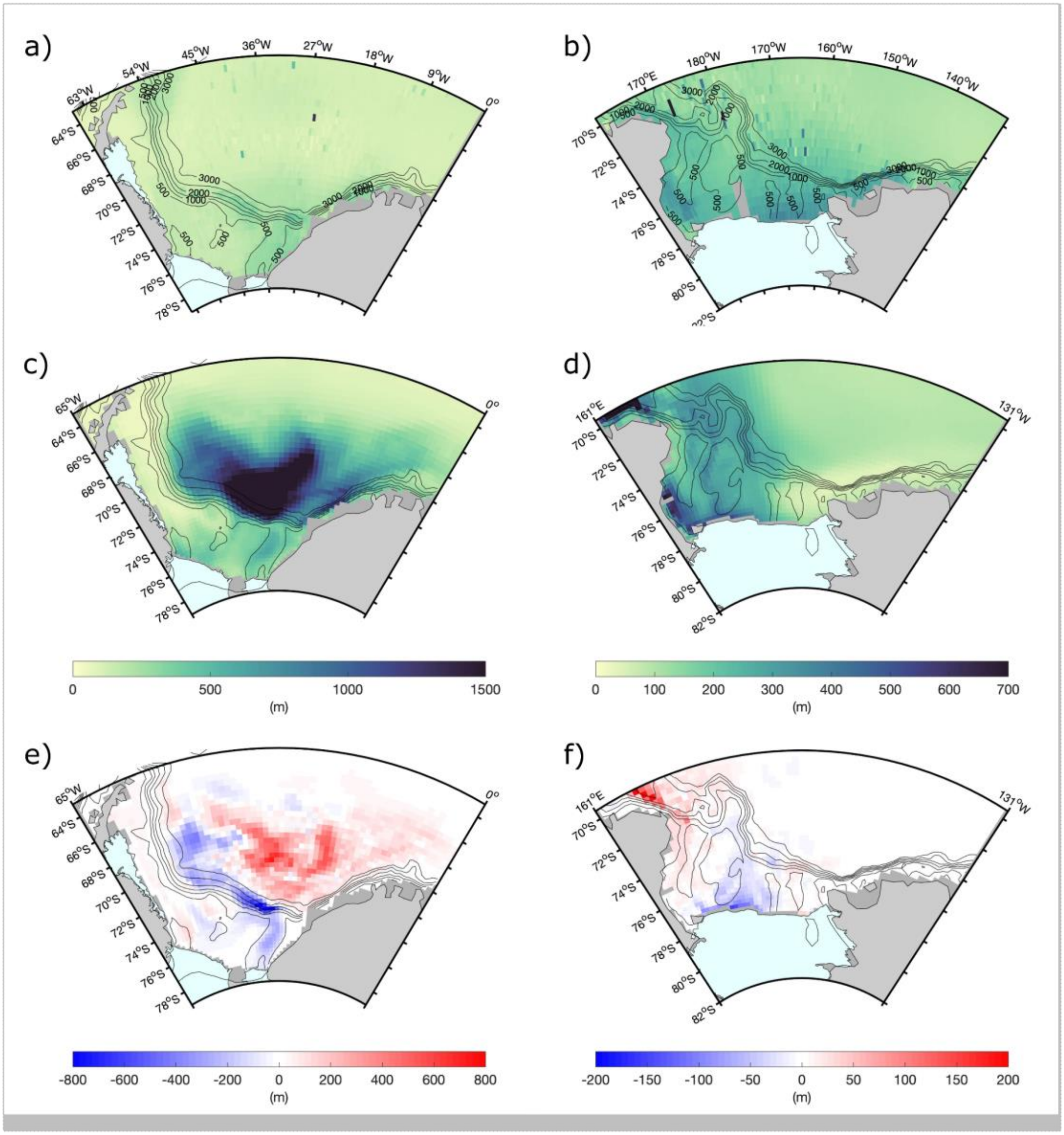
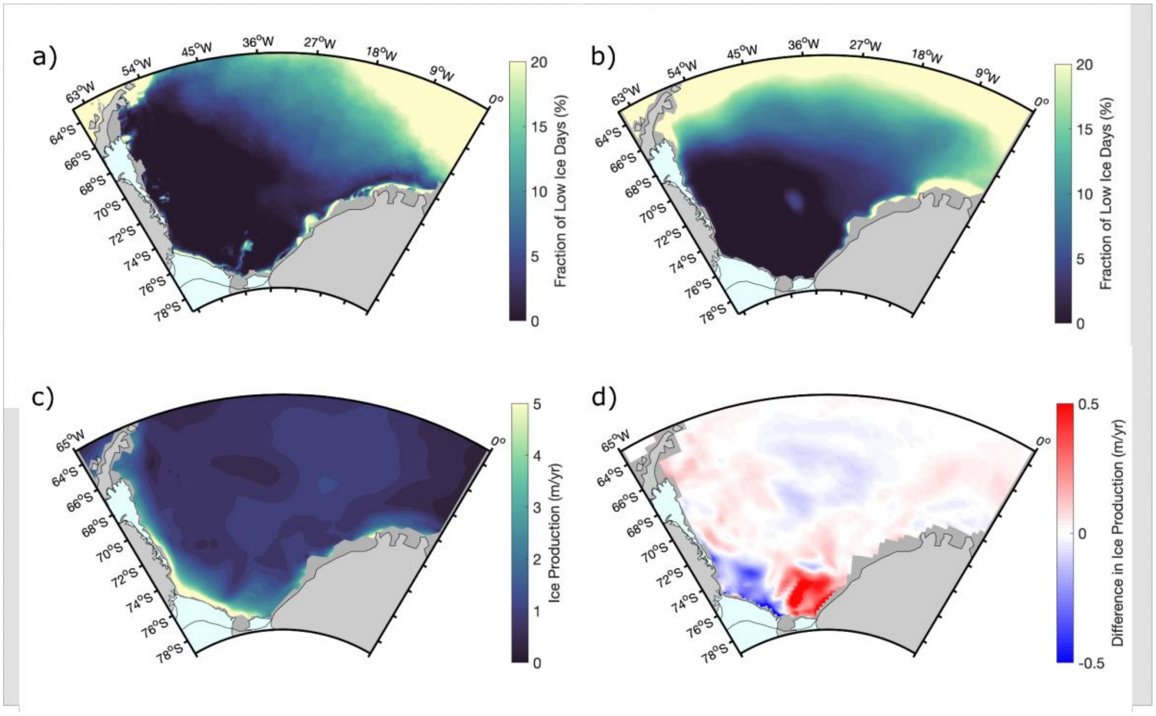
Supplementary Figures



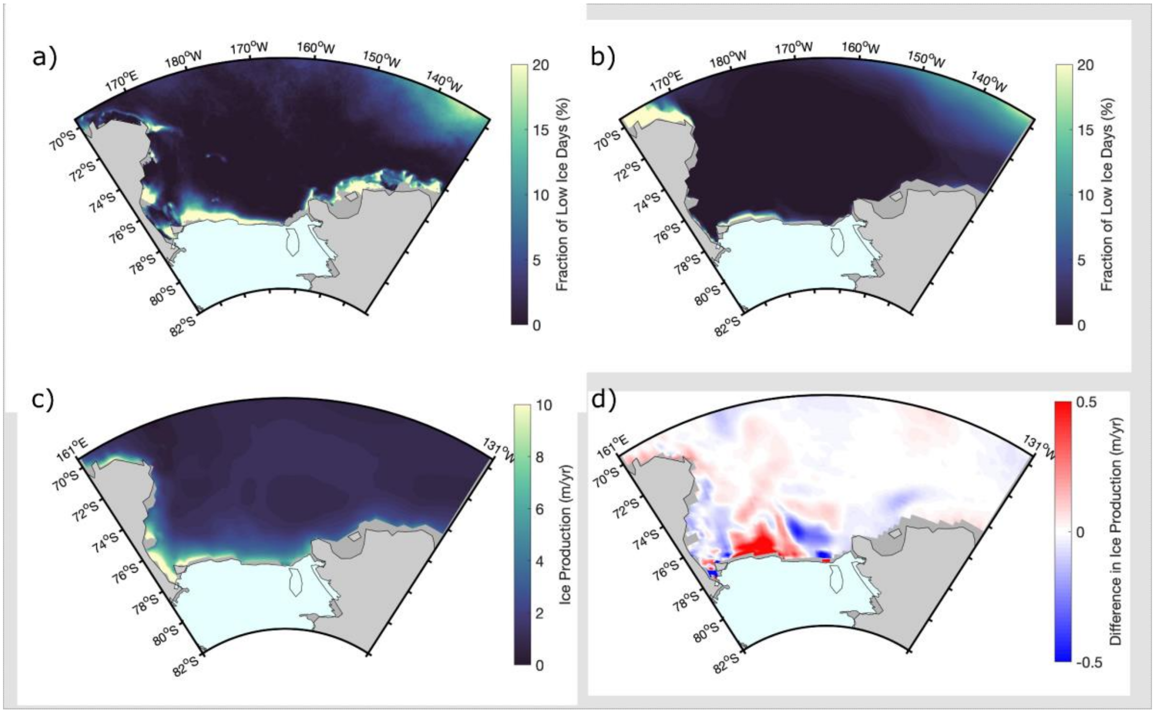
Supplementary figure 1: Difference ("Open" - "Closed") in volumetric temperature versus salinity distributions for (a) the Weddell Sea (80°S-60°S ; 65°W-20°E) and (b) the Ross Sea (85°S-68°S; 130°W-160°E) for model output excluding data underneath the ice shelves. The green boxes delimit the properties corresponding to AABW.



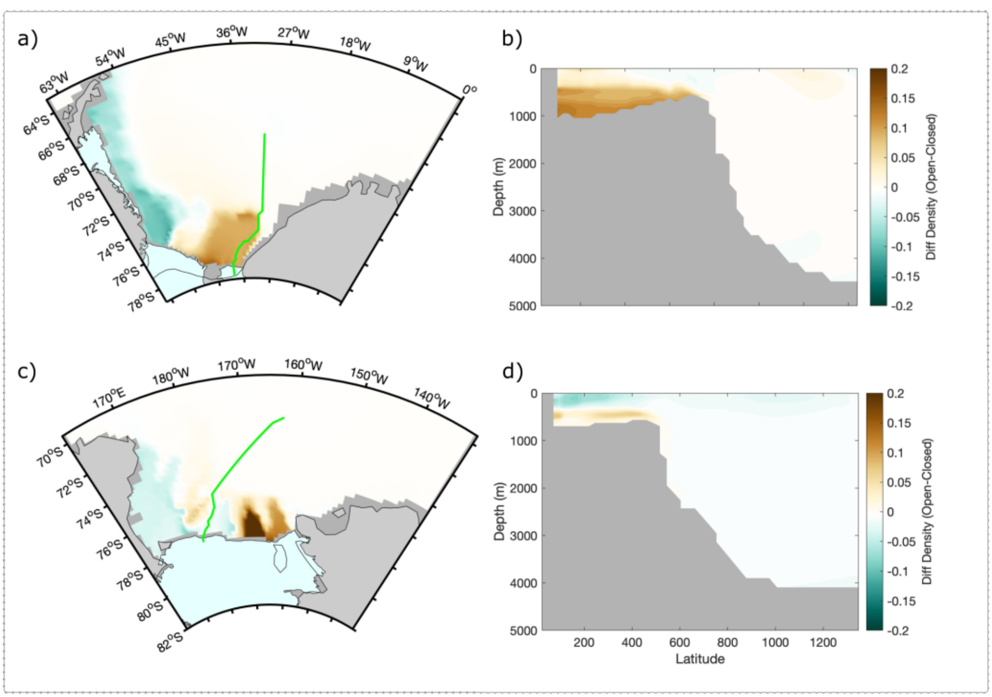
Supplementary Fig. 2: Winter mixed layer depths (MLD) from observational atlas of Sallee et al. (2021) shown in (a) and (b) for the Weddell and Ross Sea respectively, are compared with the winter mean from NEMO v4.2 eORCA1 forced model reference configuration equivalent years 1971-2009 in (c) and (d). The differences in MLDs between the "Open" cavity run and reference "Closed" run are shown in subplots (e) and (f).



Supplementary Fig. 3: The fraction of low ice days for the period 2003-2009 for (a) satellite AMSR observations (Melsheimer et al., 2020) and (b) the NEMO "Closed" cavity reference configuration. Plot (c) shows the annual mean ice production in NEMO "Closed" configuration and (d) shows the difference in ice production between the "Open" and "Closed" cavity run (Open-Closed).



Supplementary Fig. 4: Same as S3 but for the Ross Sea



Supplementary Fig. 5: Density (kg/m3) plots for the Weddell (a-b) and Ross (c-d) Seas with bottom density in subplots (a) and (c) and the cross sections of the Filchner and Challenger troughs illustrated by green lines shown in subplots (b) and (d).

Supplementary Material

S1 An evaluation of ice production and polynya activity in the NEMO simulations

S1.1 Scope

Sea ice growth, melt and drift exert an influence on water mass properties, according to many observational and model studies. In particular, near the Ronne and Ross ice shelf margins of interest for this study, during the cold season, large polynyas source dense saline waters to the surface ocean. In this Supplementary Material, we provide an evaluation of polynya activity in these two locations from our simulations and address: (i) how realistic polynya activity is; (ii) how polynya activity changes in response to the opening of cavities; and (iii) how associated changes in polynya activity affect biases in simulated water mass properties.

S1.2 Methods

As an observational basis, we use the daily ice concentration 6.25 km resolution AMSR-E ASI product (Melsheimer and Spreen, 2020), best suited to the study of polynyas with its high resolution and daily coverage. From this, following Massom et al (1998), we diagnose annual polynya activity from the *fraction of low-ice days*, namely the fraction of days with ice concentration < 75 % over a 180-day period (days 91-270, i.e. April-September). From annual values, we compute the 2003-2009 mean, mapped in Figs. S3a and S4a for Weddell and Ross Sea regions, respectively.

We compute a comparable diagnostic from model daily ice concentration outputs, whose 2003-2009 average in the “Closed” simulation is mapped in Figs. S3b and S4b.

We supplement these diagnostics with simulated annual ice production, computed as the total volume of ice produced per unit area each year. Figs. S3c and S4c map 2003-2009 averages for the “Closed” simulation and Figs. S3d and S4d show the “Open”-”Closed” difference.

We also calculate yearly ice production summed over each polynya region and compare the results with observational counterparts in the Supplementary Table below.

Ice production (10^9 m^3)	Nakata et al. (2021)	Closed	Open
Ronne Polynya	58 ± 21	24	29
Ross + Terra Nova Bay Polynya	387 ± 41	368	357

Supplementary table 1: Comparison between observational estimates and the NEMO eORCA1 configuration "Closed" and "Open" cavity runs for net ice production in Ronne Polynya of the Weddell Sea and the sum of Ross and Terra Nova Bay polynyas of the Ross Sea.

S1.4 Evaluating polynya activity

The observed fraction of low ice days indicates polynya activity at the expected locations (see, e.g., Nakata et al, 2021). In the Weddell Sea, this includes the Ronne Polynya off Ronne Ice Shelf (Fig. S3a); in the Ross Sea, this includes the Ross and Terra Nova Bay polynyas (Fig. S4a) and smaller polynyas further north. This corresponds to where we observe hyper-saline bottom waters (Figs. 2f and 3f).

Unlike observations, the simulated fraction of low ice days shows no apparent polynya activity along the ice-shelf fronts (Figs. S3b and S4b). We argue that this discrepancy is due to inconsistencies between the way the model and observations define ice concentration. Indeed, in the model, sea ice drift (aka *dynamics*), then growth and melt (aka *thermodynamics*) are calculated sequentially, at each time step. In this context, any dynamically-driven opening in the ice is, under the action of sufficiently cold air, instantaneously frozen by model thermodynamics, with thin ice. Such thin ice contributes to ice concentration as ice of any thickness, explaining why simulated concentration can be nearly 100 % in polynya regions. Satellite retrievals of ice concentration possess inherent differences with model estimates. First they have much higher resolution. Second, they contrast thick ice and open water fairly well and do not suffer from the closing effect described above. All this contributes to lower ice concentration in polynya regions in satellite products as compared with NEMO output. An additional contributing factor might be that thin ice and open water are hard to distinguish, such that some thin ice might be counted as open water in satellite products, as has been shown to occur for at least some sea ice passive microwave (PMW) algorithms (Kern et al., 2022).

From simulated ice production, Ronne (Fig. S3c), Ross and Terra Nova Bay (Fig. S4c) polynyas have a clear signature in the model, at the approximate locations inferred from the observed low-ice-day fraction. Fairly similar patterns are seen in simulated ice thickness fields (not shown), with very thin (<25 cm) ice found where polynas are deemed active. For these reasons, we surmise that there are active polynyas in our simulations, but that the fraction of low-ice days is a poor diagnostic for their identification. Instead, ice production captures the polynya activity and most importantly reflects their impact on water-mass transformation.

Annual ice production maps also indicate possible errors in the distribution of simulated polynya activity. In particular, the Ross Sea Polynya seems too narrow, whereas the Terra Nova Bay polynya seems too wide, especially north of McMurdo Sound, possibly due to the lack of landfast ice in the simulations north of McMurdo Sound (Fraser et al., 2021).

Annually-integrated ice production in the Ronne Polynya under-estimates observations. By contrast, ice production in the Ross and Terra Nova Bay polynyas is consistent with the observational estimate, though the simulated production rate is based on too large an area.

S1.5 Effect of opening cavities on polynya activity

Opening cavities is associated with changes in ice production close to the polynya regions. Overall, the annually integrated ice production (Supplementary Table 1) only slightly changes because the net effect is a residual between roughly equal areas of ice production decrease (to the west of the ice shelves) and increase (to the east of the ice shelves). It is hard to conclude on more or less realistic polynya activity in the "Open" simulation.

Changes in ice production due to opening cavities are largely consistent with patterns of temperature and salinity adjustments. Ice production is lower where temperature is higher and salinity is lower. This is consistent with circulation-induced ocean temperature changes forcing an alteration in ice production, with possible feedback on salinity. In the Weddell Sea, a re-organisation of the shelf circulation to subduct HSSW under the ice shelf reduces the ice production in the Ronne Depression and increases it to the east over the Filchner Trough. The pattern of sea ice change in the Ross Sea is less homogeneous east-west, with a reduction in Terra Nova Bay and in front of Roosevelt Island and an increase in sea ice over the Challenger Trough which is where ice shelf water (ISW) is exported.

S1.6 Summary

In summary, ice production in polynya regions decreases west of the ice shelves and mostly increases east of them when opening cavities. The decrease to the west may contribute to a reduction of the high salinity bias there. On the eastern side, increased ice production and brine rejection combines with northward export of cold ISW from the under-ice cavities. The resultant effect in the Weddell Sea is a strong east-west temperature and salinity difference (Fig. 2i). In the Ross Sea, on the other hand, increased brine rejection seems compensated by anomalous export of relatively fresh water from under the ice shelf (Fig. 3i).

Data

The AMSR-E ASI sea ice concentration data used can be found at: https://doi.pangaea.de/10.1594/PANGAEA.919778

Bibliography

Nakata, K., Ohshima, K. I. and Nihashi, S.: Mapping of active frazil for Antarctic coastal polynyas, with an estimation of sea-ice production, Wiley Online Library, 2021.

Melsheimer, C. and Spreen, G.: AMSR-E ASI sea ice concentration data, Antarctic, version 5.4 (NetCDF) (June 2002 - September 2011), https://doi.pangaea.de/10.1594/PANGAEA.919778, 2020.

Massom, R. A., Harris, P. T., Michael, K. J. and Potter, M. J.: The distribution and formative processes of latent-heat polynyas in East Antarctica, Cambridge University Press, 1998.

Fraser, A. D., Massom, R. A., Handcock, M. S., Reid, P., Ohshima, K. I., Raphael, M. N., Cartwright, J., Klekociuk, A. R., Wang, Z. and Porter-Smith, R.: Eighteen-year record of circum-Antarctic landfast-sea-ice distribution allows detailed baseline characterisation and reveals trends and variability, Copernicus GmbH, 2021.

Kern, S., Lavergne, T., Pedersen, L. T., Tonboe, R. T., Bell, L., Meyer, M. and Zeigermann, L.: Satellite passive microwave sea-ice concentration data set intercomparison using Landsat data, Copernicus GmbH, 2022.