Answer to comments by reviewer #1

The formation of deep and bottom waters on the continental shelf in the Weddell Sea is a key mechanism for sequestering carbon and exporting heat to the abyssal layer. This study by Nissen et al. explores the pathways of warm waters onto the shelf and dense waters flowing off the shelf under both historical and future conditions. They used output from the global ocean-sea ice model FESOM-1.4 to conduct Lagrangian experiments in the Weddell Sea in 1990-2009 (historical period) and in 2080-2099 under the high-emission scenario SSP5-8.5 (future period). The depth where particles reach the Filchner Ice Shelf front and where they originated in the open ocean and crossed the shelf break is evaluated as well as the pathways. In the historical period, particles mostly reach the ice shelf front within the upper 200 m and originate from the upper open ocean, suggesting weak inflow of modified Circumpolar Deep Water into deeper parts of the ice shelf cavity. Under a high-emission scenario, more particles reach the ice shelf front by the end of the 21st century, originating from greater depths offshore and reaching the ice shelf front at greater depth compared to the historical period. This increased onshore transport has important implications for future ice shelf basal melt rates and deoxygenation. In the future period, the transit time from the shelf break to the ice shelf front decreases by 6 months and cross-shelf flow becomes more likely in winter. Particles leave the Filchner Ice Shelf front mostly below 600 m (that would be within the ice shelf cavity), flow down the western shelf break of the Weddell Sea and enter the open ocean as dense waters mostly below 800 m. In the future period, the particles trajectories are overall shallower and especially in the open ocean the depth reached by the particles is greatly reduced with only 60% below 500 m and none below 1500 m, but their horizontal distribution is similar. Most particles reside on the shelf for a year and leave the shelf in autumn and winter in the historical period, while in the future period the median residence time on the shelf is 21 months and spring is as important as winter for the export across the shelf.

This is an interesting study and important contribution regarding the cross-shelf transport in the Weddell Sea using Lagrangian methods for the first time. The manuscript is very well structured and written with the figures illustrating the results and supporting the conclusions. I have a few minor suggestions which might help to further improve the manuscript.

As a paper should be self-contained, more details should be given when referring to results from your previous papers (Nissen et al., 2022, 2023) which are fundamental for understanding the conclusions. Especially the mechanisms for the changing pathways in the future period are not discussed in much detail and this leaves readers with open questions when they are not fully aware of these previous studies. Overall, I think that this manuscript is a valuable contribution to the community and should be published in Ocean Science after some minor revisions detailed below.

We thank the reviewer for the positive feedback on our study. We have revised the manuscript according to the reviewer’s comments and suggestions. Please see below for more detail.

Specific comments:

ll. 6-11: Rearranging these sentences (and potentially including additional results) would clarify the results and the conclusions made. The results should be described more clearly by e.g., referring to depth changes in meters as well. In addition, the implications could directly follow individual results and not be stated a few sentences afterwards.

We have modified this part of the abstract as suggested, and it now reads:

“We show that particles reaching the ice-shelf front from the open ocean originate from 173% greater depths by 2100 (median; 776 m as compared to 284 m for the present-day), while waters leaving the cavity towards the open ocean end up at 35% shallower depths (550 m as compared to 850 m for the present-day). Pathways of water leaving the continental shelf increasingly occur in the upper ocean, while the on-shelf flow of waters that might reach the ice shelf cavity, i.e., at deeper layers, becomes more important by 2100. Simultaneously, median transit times between the Filchner Ice Shelf front and the continental shelf break decrease (increase) by 6 (9.5) months in the backward (forward) experiments. In conclusion, our study demonstrates the sensitivity of regional circulation patterns in the southern Weddell Sea to on-going climate change, with direct implications for ice-shelf basal melt rates and local ecosystems.“

ll. 84-85: A few sentences should be added on what has been evaluated in Nissen et al. (2022, 2023) and what biases were found to make the paper more self-contained.

We have added a sentence summarizing the outcomes of earlier evaluations of the model simulation:

“Acknowledging that the strength of the Weddell Gyre in the FESOM1.4 simulation is biased low compared to estimates based on Argo floats (Reeve et al., 2019), water-mass distributions and water-mass transformations were shown to overall agree well with observations. In the context of this study, we note the high-density bias of the WDW core in the open ocean, which possibly makes the southern Weddell Sea continental shelf too susceptible for an on-shelf flow of WDW during the 21st century.”

ll 174-176: Be more specific about the mechanisms detected in Nissen et al. (2022, 2023), e.g., increasing on-shelf heat transport with negative cross-shelf break density gradient in future period.

We have added a sentence to explain the mechanisms at play:

“The overall enhanced future on-shelf transport is facilitated by a reversal of the cross shelf-break density gradient by the end of the 21st century (Nissen et al., 2023).”

Figures 2 and 6: These figures illustrate the results really well, but they could be improved. The thickness of the arrows doesn’t seem to be “scaled with the relative importance of different depth intervals for the origin of these waters before the crossing and their fate after the crossing, respectively”, as stated in the figure caption. For example, in Fig. 2a the thick blue and yellow arrows representing flow from the open ocean on to the shelf in the upper layer should represent about 80% of the particles but this is not represented by their combined thickness. Can you depict the changes in the vertical distribution offshore better by changing the position of the arrow at the right axis of panel a and e? For example, in Fig. 6e the red arrow should point at a shallower depth offshore (approximately 600-700m) compared to panel a. In my opinion the size of the figure is too small, especially the text in panel a and e is hard to read, and the lower panels should be enlarged. This could be achieved by having the panels corresponding to the historical and future simulations in separate rows instead of columns.

We appreciate the reviewer’s feedback and suggestions. We have revised the Figure by making better use of white spaces and by increasing font sizes in all panels (see Fig. 1 & 2 below). We note that there was a misunderstanding in how the arrow thickness is scaled in this figure. The scaling corresponds to the relative contributions within each color, i.e., within each depth interval at the shelf-break crossing. This means that the scaling of the blue and yellow arrow in the upper layer cited by the reviewer are scaled relative to their contribution to particles crossing the shelf in the upper (blue) and middle (yellow) layer, respectively. Their thickness thus indicates that the vast majority of the particles crossing the shelf break in the upper and middle layer originate from the uppermost layer in the open ocean. We have revised the figure caption to enhance clarity. The respective sentence in the Figure captions of the revised Fig. 2 & 6 in the manuscript reads:

“The arrows are colored depending on the depth level at the shelf-break crossing, and for each color, their line thickness is scaled with the relative importance of different depth intervals for the origin of these waters before the crossing and their fate after the crossing, respectively.“

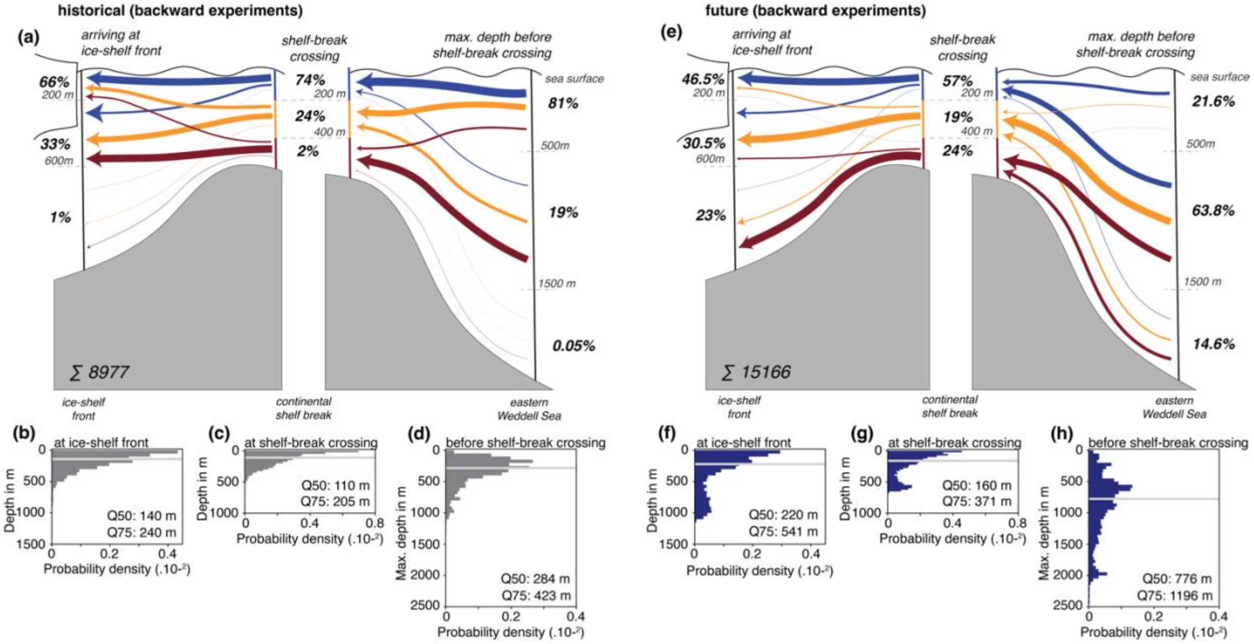

Fig. 1: Revised Fig. 2 of the manuscript.

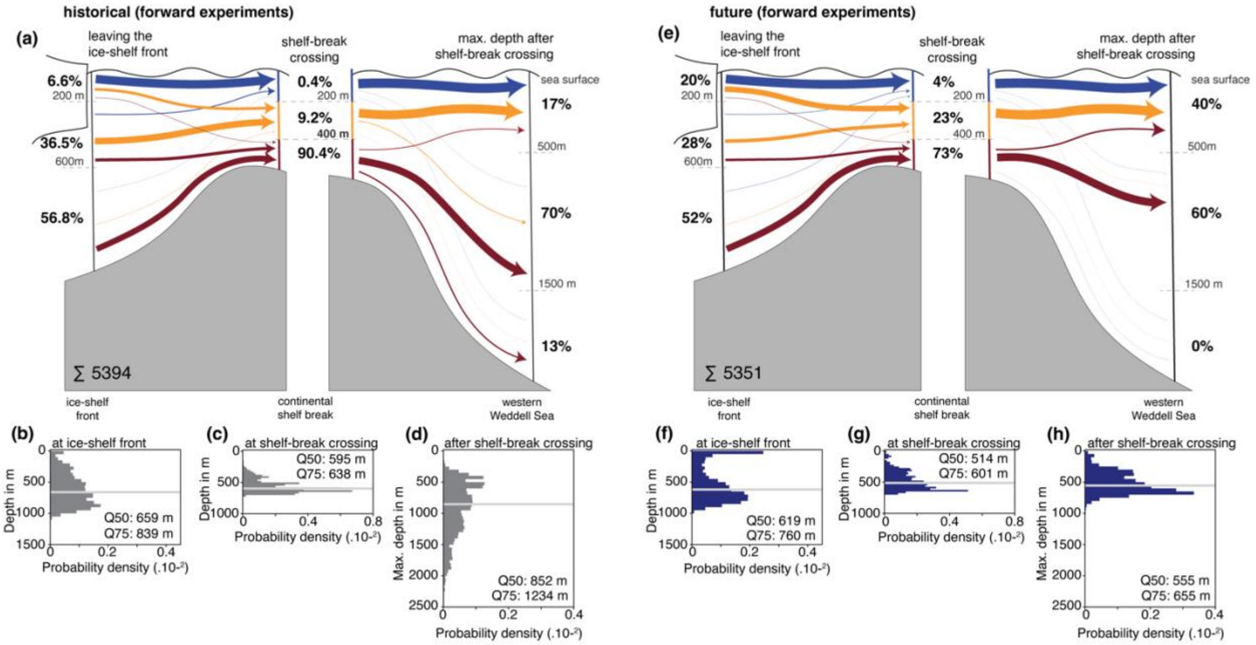

Fig. 2: Revised Fig. 6 of the manuscript.

ll 271-273: Be more specific about what changes were detected in Nissen et al. (2022), e.g., reduced ventilation rate along the slope, reduced surface water mass transformation and decline in density in future period.

We have added a sentence to explain the mechanisms at play:

"The reduced density of newly formed dense waters is mainly caused by the freshening of waters on the continental shelf as a result of reduced sea-ice formation and enhanced ice-shelf basal melt and results in reduced ventilation of bottom waters along the Weddell Sea continental slope (Nissen et al., 2022)."

Technical comments:

caption of Fig. 1: Include description of black and grey contours in the figure caption.

Changed as suggested, and the respective part of the new caption reads:

"Blue colors display the bottom topography in the area (based on RTopo-2; Schaffer et al., 2016), while the black and grey lines denote the 700 m isobath and the ice-shelf front, respectively."

ll 309: Be more specific, what percentage of particles is referred to as "sizeable"?

We rephrased this sentence to now read:

"Specifically, the maximum depth that particles reach after leaving the continental shelf in our forward experiment exceeds 3000 m, and ~13% of particles reach a depth >1500 m for the historical period."

Answer to comments by reviewer #2

This is a fine study with a focus on the Weddell Sea. It is well written and the only complains I have is that is that the reader is expected to fully trust the model. To do so, she must be given much more details.

We thank the reviewer for the positive feedback on our paper. Please see below for details on how we have incorporated all comments into the revised version of the manuscript.

line 83: What is the quality of the present day forcing? It seems to come from a coupled model, so there should be figure with biases in sea-ice and winds at least.

Semmler et al. (2020) assessed the contribution of the AWI Climate Model (AWI-CM) to the 6th phase of the "Coupled Model Intercomparison Project" (CMIP) in detail and showed that the AWI Climate Model outperforms the CMIP5 multi-model average in representing atmospheric quantities such as winds or temperature, especially in the Antarctic. Nonetheless, biases remain compared to observations. A comparison of the simulated winds in the AWI-CM used to force the ocean-only model simulations in this study to the ERA5 reanalysis between 1990 and 2009 (Hersbach et al., 2023) reveals that the average winds in the AWI-CM are too strong over the Weddell Sea (Fig. 1 below). Further, a comparison of the simulated average sea-ice concentrations between 1990 and 2009 in FESOM1.4 to the NOAA/NSIDC Climate Data Record of passive microwave sea-ice concentration (Meier et al., 2021) reveals that the average sea-ice cover is too low throughout the Weddell Sea, in particular in the open ocean in the northwestern Weddell Sea near the Antarctic Peninsula (up to 25% too low; Fig. 2 below). Acknowledging a negative bias of similar magnitude on the southeastern Weddell Sea continental shelf (possibly facilitated by too strong offshore winds in the area, see Fig. 1 below), average sea-ice concentrations are overall better simulated on the southern continental shelf than in the open ocean.

In the revised manuscript, we have added the following sentence to the method section:

"Semmler et al. (2020) showed that the AWI Climate Model outperforms the CMIP5 multi-model average in representing atmospheric quantities such as winds or temperature for the period 1985-2014 in the Antarctic. Compared to ERA5 reanalysis (Hersbach et al., 2023), simulated near-surface winds in the AWI Climate Model are overall stronger in the Weddell Sea. "

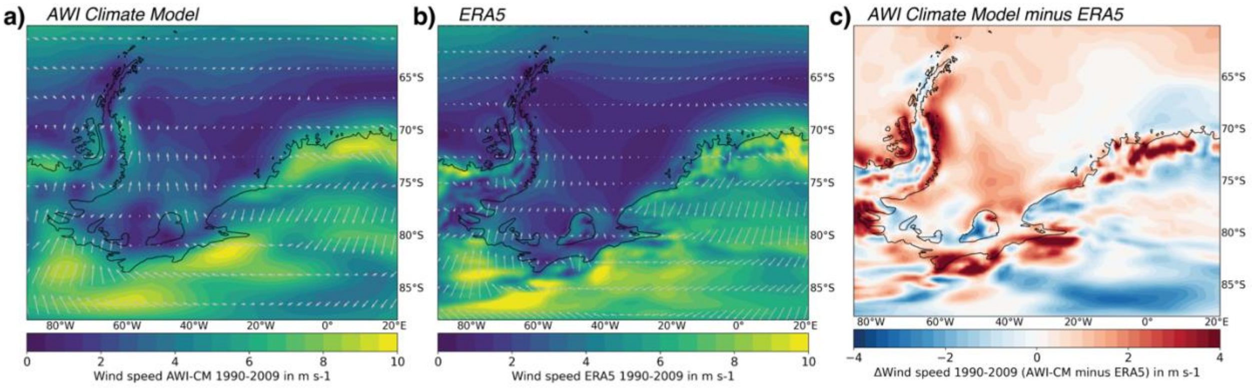

Fig. 1: Averaged near-surface winds between 1990 and 2009 in a) the AWI Climate Model used to force the ocean-only model experiments in our study and b) ERA5 (Hersbach et al., 2023). Colors denote the average wind speed, and wind direction is shown by the grey arrows. Note that the wind direction is not shown for every available grid cell to enhance readability of the figure. c) Difference in wind speed between panel a) and b).

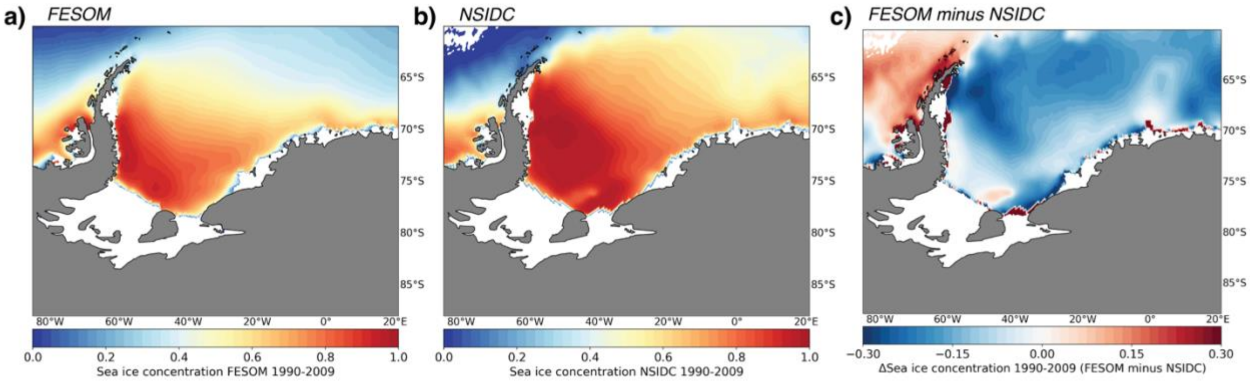

Fig. 2: Average sea-ice concentration between 1990 and 2009 in a) FESOM used in our study and b) the NOAA/NSIDC Climate Data Record Version 4 (Meier et al., 2021). c) Difference in sea-ice concentration between panel a) and b). Fields were interpolated to the same regular mesh for better comparability, note the unrealistic interpolation artefacts near the ice-shelf front in all panels.

What is fidelity of the ocean circulation? Can you show a comparison with some data, in particular with velocity- if available?

Evaluating ocean circulation at high latitudes is still difficult due to the scarcity of observations, especially on and near the Antarctic continental shelf. Reeve et al. (2019) report volume transports based on Argo floats across a variety of transects in the open-ocean Weddell Sea. Overall, in comparison to these data, the simulated volume transports in FESOM1.4 are biased low. The average inflow across the prime meridian in the eastern Weddell Sea south of 65°S amounts to 5.6 Sv in FESOM1.4 (based on monthly-averaged velocity fields 1990-2009), which is lower than the inflow suggested by the float data (17±3 Sv). We note that substantial seasonal variability in the inflow has been reported based on ship-based data (2-24.4 Sv; Cisewski et al., 2011). In FESOM1.4, in agreement with these observations, the inflow is strongest in winter (June-August), when it amounts to 11.8 Sv. Similarly, the outflow in the northwestern Weddell Sea west of 45°W is strongest in winter when it amounts to 17.4 Sv (1990-2009). Averaged over the whole year, the simulated transport in FESOM1.4 amounts to 10.9 Sv, i.e., just below the range indicated by the float-based observations (18±6 Sv; Reeve et al., 2019). North of the Weddell Sea, the simulated transport across Drake Passage between 1990 and 2009 lies within the range suggested by an observation-based estimate (Donohue et al., 2016; Fig. 3 below). In the revised manuscript, we have included information on the evaluation of simulated velocities in the method section (also in response to a comment by reviewer #1):

“Acknowledging that the strength of the Weddell Gyre in the FESOM1.4 simulation is biased low compared to estimates based on Argo floats (Reeve et al., 2019), water-mass distributions and water-mass transformations were shown to overall agree well with observations.”

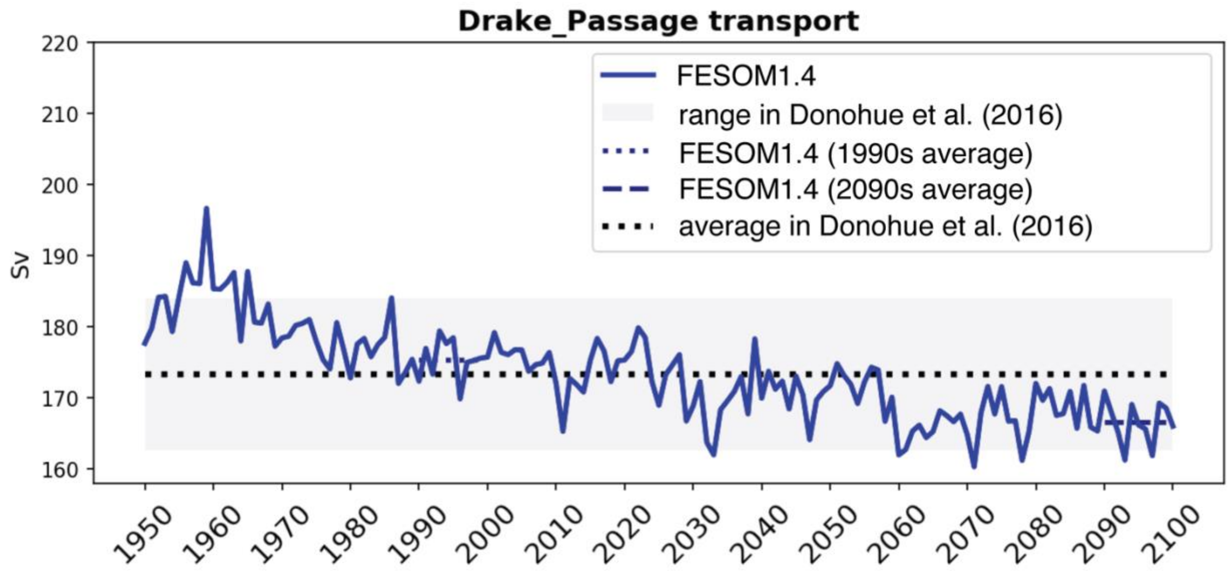

Fig. 3: Water-column integrated transport across Drake Passage in FESOM1.4 (historical + SSP5-8.5 scenario) in blue as compared to an observation-based estimate for the period 2007-2011 from Donohue et al. (2016). The dotted black line and the grey shading represent the mean and range of the observation-based transport, respectively.

The model has some 5km resolution, so if the particles are advected with daily (mean, snapshots?), the structure of the mesoscale is lost. Does that matter? What is the advection time step?

In our experiments, the Lagrangian particles are advected with a time step of one hour using daily-averaged velocity fields from the model (see methods of the paper). In agreement with the reviewer, we acknowledge that by using daily-averaged model output, some structure of the mesoscale is not resolved by the velocity field underlying our Lagrangian experiments. The effect of not fully resolving the mesoscale on the results cannot be quantified without further model simulations to store the simulated velocity fields at higher frequency, for which we unfortunately do not have the computational resources. However, we note that all Lagrangian experiments in our study are likely affected in a similar way by this shortcoming. Assuming that the projected long-term change in the mean current field outweighs any change in shorter-term variability, the impact of not fully resolving the mesoscale on the results presented in this paper are therefore probably small.

In the revised manuscript, we have included a statement on this in the limitation section:

"Lastly, by using daily-averaged velocity fields to advect Lagrangian particles, we acknowledge that the mesoscale is not fully resolved. Yet, as all of these points can be expected to impact both time slices in a similar manner, we assume the qualitative results of our study to only be marginally affected by these limitations."

Section 4. I would probably move it to section 2.1, as part of the model setup. Your statements here suggest that open ocean convection is not important in the Weddell Sea, and the z - levels make a downslope current unlikely. So how do the particles get deeper? Is it simply flow along isopycnals? Or are they advected across density fronts (see comment above)? Can you provide a plot that shows some of particle trajectories in a vertical plane?

In our Lagrangian experiments, particles are advected with a 1-hourly time step using the resolved velocity fields from FESOM1.4, meaning that particles can only get deeper (shallower) when the model resolves a downward (upward) movement in the vertical velocity component. As illustrated by the example trajectories shown in Fig. 4 and Fig. 5, particles are often advected across isopycnals while moving upwards or downwards. At the same time, other particles moving downward show little change in density along their respective trajectory (Fig. 4), demonstrating the existence of downslope currents along isopycnals despite using a z level coordinate in the model. Lastly, while we appreciate the reviewer’s suggestion on the location of the limitation section, we have decided to keep the section at its current location in the manuscript.

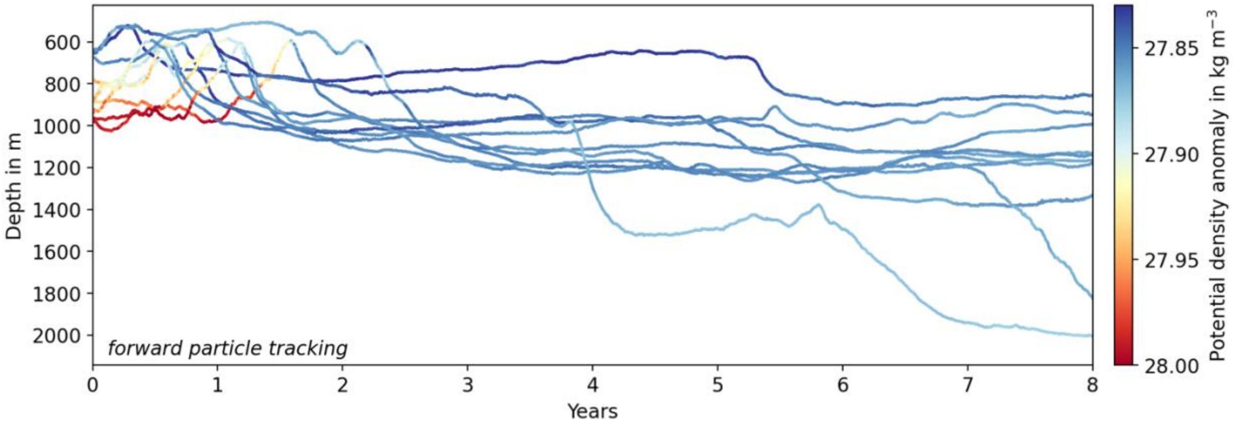

Fig. 4: Ten randomly-chosen example trajectories as a function of depth from the present-day time slice of the forward particle tracking experiment. Trajectories are colored as a function of the potential density anomaly along their path.

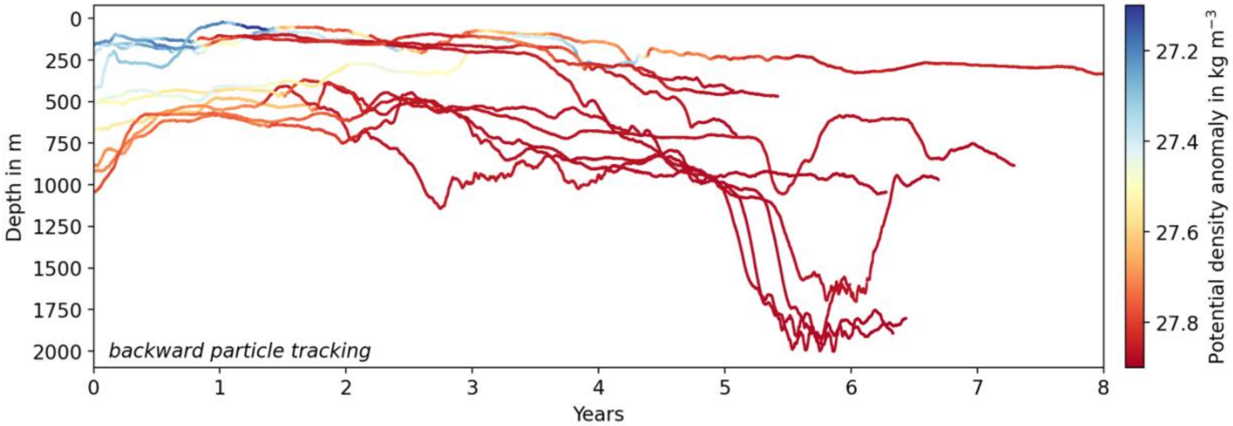

Fig. 5: Ten randomly-chosen example trajectories as a function of depth from the future time slice of the backward particle tracking experiment. Trajectories are colored as a function of the potential density anomaly along their path.

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Cisewski, B., Strass, V. H., & Leach, H. (2011). Circulation and transport of water masses in the Lazarev Sea, Antarctica, during summer and winter 2006. *Deep-Sea Research Part I: Oceanographic Research Papers*, *58*(2), 186–199. https://doi.org/10.1016/j.dsr.2010.12.001

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Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (Accessed on 06-Nov-2023)

Meier, W. N., F. Fetterer, A. K. Windnagel, and J. S. Stewart. (2021). NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 [Data Set]. Boulder, Colorado USA. National Snow and Ice Data Center. https://doi.org/10.7265/efmz-2t65. Date Accessed 11-06-2023.

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