Tromsø,
10.07.2024

Response to the comments from Anonymous Referee #1 on “Hydrography and circulation below Fimbulisen Ice Shelf, East Antarctica, from 12 years of moored observations”

We thank Anonymous Referee #1 for their constructive and extensive comments on our manuscript. Below, we have copied the comments, and we give our replies in blue color. As we do not submit a revised manuscript at this stage, we respond to the referee’s major comments from the discussion window, but not to the more detailed comments in the uploaded manuscript PDF. We have gone through these comments, too, and agree with a great majority of them. We will give a response to every single comment at a later stage along with a revised manuscript.

Review of Hydrography and circulation below Fimbulisen Ice Shelf, East Antarctica, from 12 years of moored observations By Lauber et al

The authors describe in detail data from three moorings that were deployed in 2009 in the ocean cavity beneath Fimbulisen. Each mooring consisted of two sets of instruments, one within 50 m or so of the ice base, and the other somewhat deeper in the water column. The (up to 12-year long) time series were supplemented with ship-based data from up stream of the study sites: CTD sections and two moorings.
The authors find that the cavity is primarily ventilated by Winter Water (WW), but Antarctic Surface Water (ASW) intrudes along the ice base at particular times of the year, and that Warm Deep Water (WDW) can enter the cavity via warm-cored eddies. Various generation mechanisms for the eddies are discussed, although no evidence for any in particular is available from the data.
The data confirm and, to an extent, extend conclusions from previous studies that use shorter versions of the time series. As the salinity data were available only up until the end of 2010, the most detailed analysis was undertaken for the data from that year. This involved partitioning the water masses observed at the moorings using an Optimum MultiParameter (OMP) analysis with dissolved oxygen (DO), temperature (T) and salinity (S) as the parameters, with four end members (WW, WDW, ASW and glacial meltwater (GMW)).
This was a very detailed read, and I'm sure I managed to lose sight of many of the links that the authors make. By the very nature of the dataset, some of the conclusions are a bit speculative, and here and there the evidence base is weak. But those statements are appropriately caveated in the text, and significant effort has been made to quantify uncertainty.
I am attaching a marked up PDF that contains all my comments except for one major one given below. Most of the comments are minor suggestions for re-wording, or requests for re-phrasing to improve clarity. All can be readily dealt with by simple changes to the text.

Thank you for taking the time to review our study and for your positive assessment.

Major comment.

I'm very concerned with the selection of ASW as an end member for the OMP analysis. Clearly, if ASW enters the cavity, and the authors do a good job of making the case that it does, then the analysis must handle it in some way. But ASW properties change during the year and it makes some of the longer term trends in Fig 6, for example, highly suspect. As the winter comes on, we would expect ASW to be cooled to the freezing point quite rapidly. In any case, there will be a strong seasonal signal to its properties. Therefore, the trends we see in Fig 6 are almost certainly a result of changes in the end member properties.

This is partly handled by the large uncertainty bounds that the Monte Carlo analysis places on the time series of concentrations, but the authors still refer to seasonal variation in the different water mass concentrations. Placing large uncertainty on the ASW end member properties doesn't solve the problem, as the properties move in a well-defined way within the box in properties space - essentially, the distribution is not Gaussian.

Perhaps the authors can explain their thinking on this point. This can be resolved by carrying out experiments to see the extent to which a likely seasonal profile in ASW properties would change end member concentrations. That would then indicate whether more caveats need to be declared.

Thank you for raising this concern. We agree that the properties of ASW change during the year, and that this likely affects our quantification of the ASW fraction inside the cavity. To explore the extent of the effect of changing ASW properties on our results, we defined, as suggested, a seasonal profile of the ASW properties for the OMP analysis. To define this seasonal profile, we used the hydrographic climatology from Hattermann (2018) and data from the Seaglider sg564, both mentioned in the manuscript. We derived ASW properties from both datasets by averaging the properties of water at a potential density below 27.6 kg m^{-3} for each available month. Oxygen data (at an offset of 1.5 ml l^{-1}, which was removed) were only available from the Seaglider between December and March, so we interpolated the values in between. The resulting seasonal cycles of the conservative temperature, absolute salinity, and dissolved oxygen of ASW are shown in Fig. R1. We used these seasonal cycles as end member properties of ASW in the OMP analysis to re-do Fig. 6 in the manuscript. We did not use a seasonal profile for any other water mass than ASW, and we kept all end member uncertainties constant with time.

Fig. R2 shows the comparison between the new (seasonal cycle on ASW properties) and the old (no seasonal cycle on ASW properties) Fig. 6 from the manuscript. Adding the seasonal cycle to the ASW properties increases the values of the maximum ASW concentrations by around 20% at $M1_{upper}$ and 10% at $M2_{upper}$. However, it does not affect the timing of the maxima and the pattern of a rapid ASW increase and a slow decrease afterward. That is, the overall temporal evolution of the water mass fractions is not sensitive to the dynamical definition of ASW, only the absolute water mass fractions are.

A T-S diagram for $M1_{upper}$ and the Seaglider shows which water at $M1_{upper}$ can be derived from ASW after interaction with the ice base, following meltwater mixing lines. Water connected to the center of the “cloud” of ASW properties in T-S space is only found in March/April at $M1_{upper}$. This is why the timing of the maximum ASW concentration is not sensitive to the exact definition of ASW, as shown in Fig. R2. During the rest of the year, the meltwater mixing lines indicate that the water at M1$_{upper}$ is derived rather from winter water, although some mixing lines still cut the side of the ASW cloud, giving some remaining fraction of ASW independent of if it is given a seasonal profile or not.

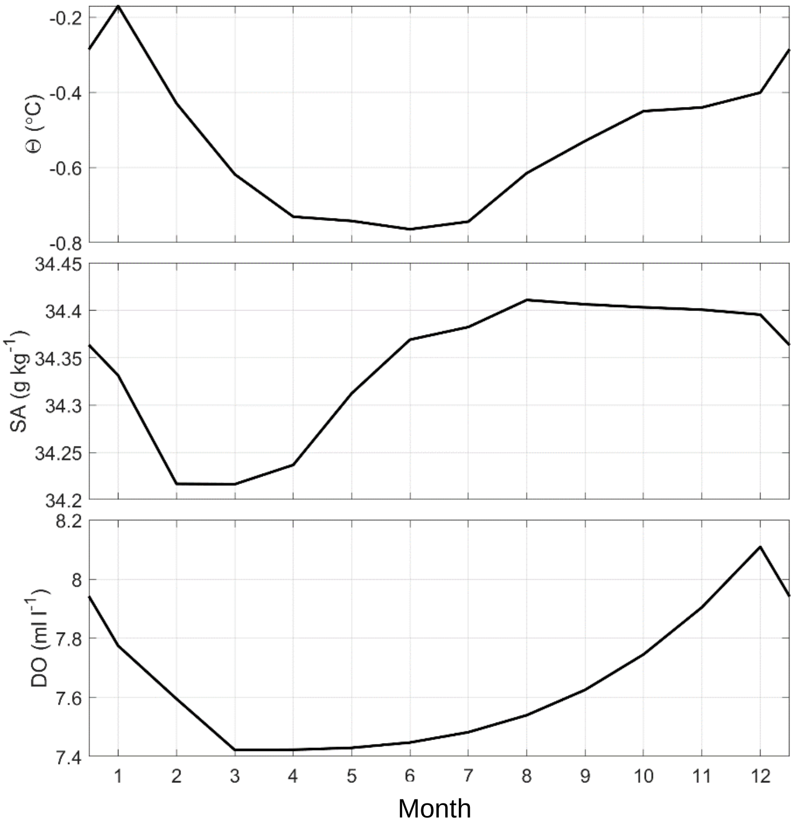

Fig. R1: Seasonal cycles of conservative temperature, absolute salinity, and dissolved oxygen derived from the data from Hattermann (2018) and the Seaglider sg564.

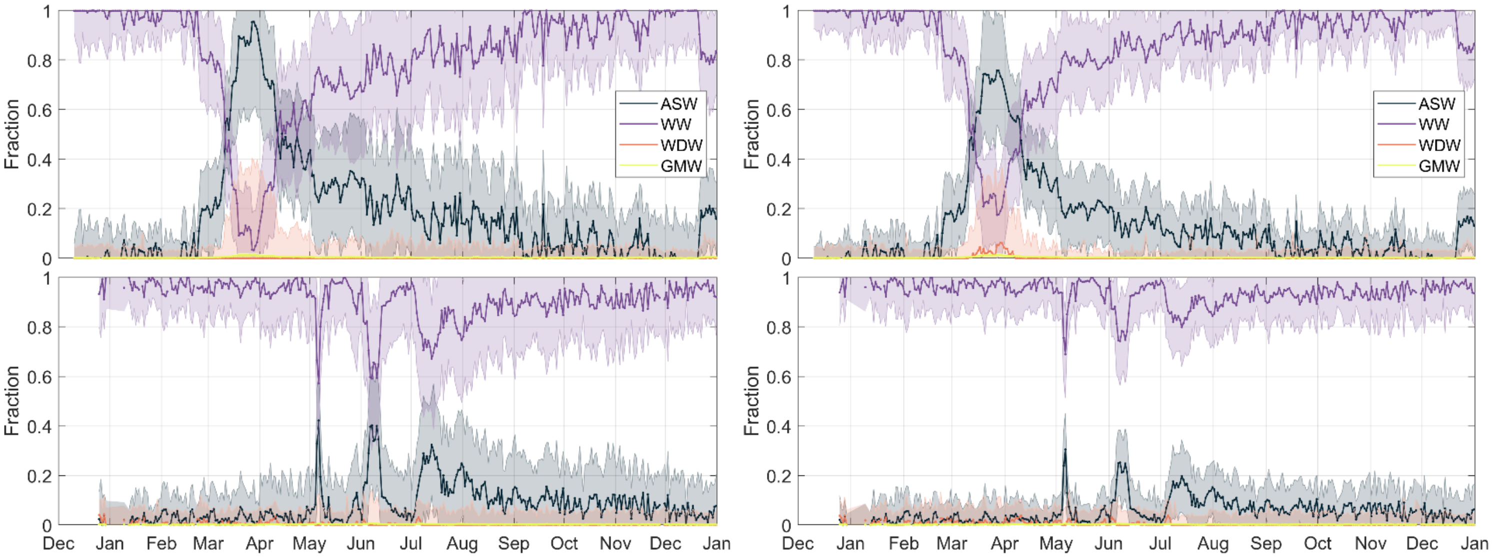

Fig. R2: Temporal evolution of water mass fractions during 2010, using a seasonal profile for ASW (left), and no seasonal profile for ASW (right).

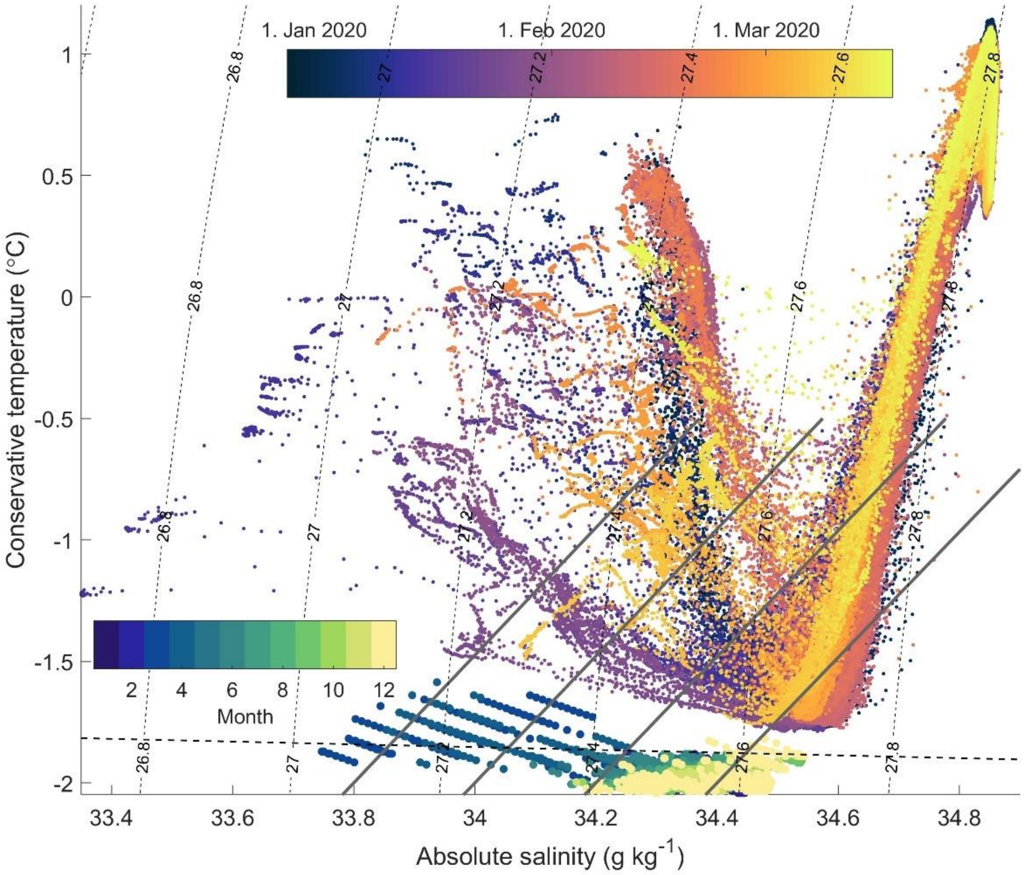

Fig. R3: Conservative temperature - absolute salinity diagram of $M1_{upper}$ (blue-green-beige colormap) and the Seaglider (sg564) presented in the manuscript (purple-orange-yellow colormap). The colors indicate the month from December 2009 and December 2010 for $M1_{upper}$, and the time from December 28th, 2020 to March 17th,2021 for the Seaglider. Grey lines are meltwater mixing lines. The thin dashed black lines show contours of the potential density anomaly, and the thick dashed black line shows the surface freezing temperature.

We acknowledge that it is a valid option to include a seasonal profile for the ASW properties. However, we believe that this method introduces some new issues:

- The seasonal changes in ASW, e.g. cooling and salinification of the ASW in autumn/winter, are related to the occurrence of WW. This collapse of ASW onto more homogeneous WW between March and July can be nicely seen in Fig. R4 (Nøst et al., 2011).
  That is, by defining the ASW properties with seasonally varying properties, we would already mix ASW and WW properties, and the separation between the end member properties would become less distinct.
- It is challenging to define a reliable seasonal cycle of ASW properties. ASW generally describes a class of water masses with a wide range of properties. Those vary not only seasonally, but also spatially (with distance from the coast, along the coast, and with depth) and interannually. Hence, even a seasonal approach for the ASW would be incomplete, facing the same problems as a single end member, with the addition of the unclear distinction with the WW.

- Seaglider sg564 data are only available from December to March, requiring interpolation in between. These data are widely spread even within a single month (Fig. R3). The data from Hattermann (2018) are generally applicable to the Fimbulisen region, but the hydrographic seasonal cycle was also shown to have a temporal offset of 1-2 months compared to 6 °E (Lauber et al., 2024).
- The seasonal cycle defined for the ASW properties is valid for the coastal open ocean. Due to downwelling at the ice front and advection to the mooring sites, this seasonal cycle is likely delayed in the cavity. This delay is not known and would have to be estimated, introducing additional uncertainties.

Due to the reasons given above, we prefer to keep the “non-seasonal” definition of ASW. This definition does not account for varying ASW properties, but one can identify when other water masses than those spanning the WW-WDW-GMW space contribute to the composition of the cavity water masses – this is the main intention of our approach, and we will highlight this intention in a revised version of the manuscript. We will introduce ASW and WW more clearly as end members of surface water that transition into each other and the properties of which seasonally vary due to air temperature and sea ice formation/melting. We will make sure to interpret the results of the OMP analysis in accordance with this definition of the water mass end members.

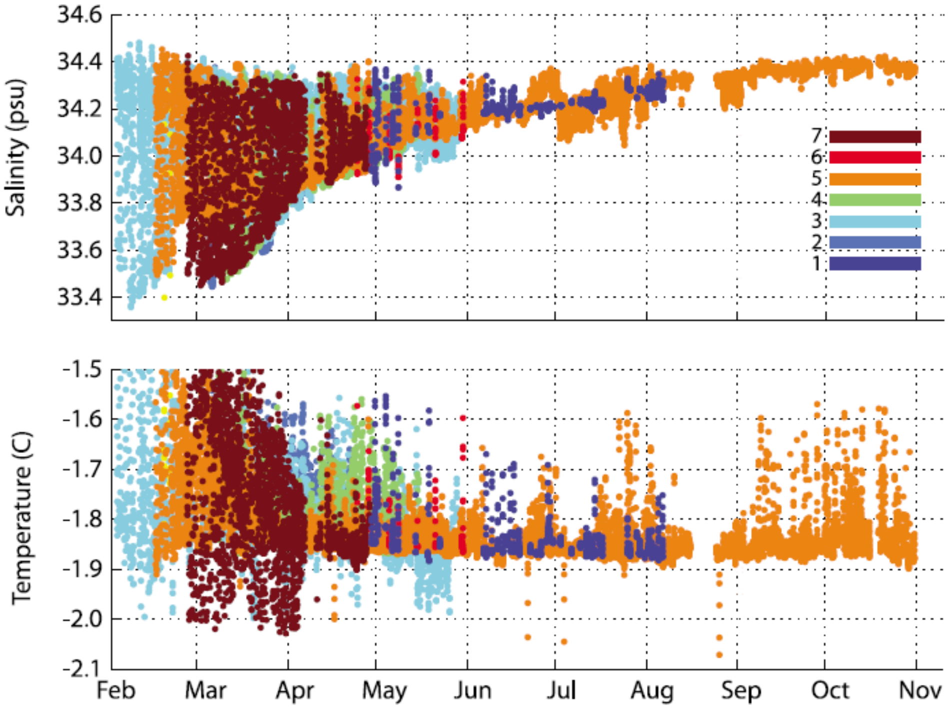

Fig. R4: Salinity and temperatures from each data point within 100 km of the ice front/coast and above the thermocline plotted against time. The individual seals are represented with colors. The figure and caption were taken from Nøst et al. (2011).

Additional remark.
Identifying the participation of WDW and ASC in basal melting is useful, but much more useful would be an attempt to quantify the contributions of WW, WDW and ASW. Or at least place bounds on the contributions. It's likely that a model would be required to extrapolate from the mooring data, but it might be possible to make progress shy of a model.

Thank you for this suggestion. It would be indeed more interesting to quantify the contributions of the water masses for basal melting.
We attempted a back-of-the-envelope calculation, using the satellite-derived basal melt rate data (mean state) from Adusumilli et al. (2020) and ice draft data from Morlighem et al. (2020). We calculated the mean basal melt rate for pre-defined depth bins in intervals of 100m and weighed these melt rates with the respective area over which the depth bins occur, giving the mean mass loss of Fimbulisen depending on the ice draft. We then interpolated our derived mean water mass concentrations at the instrument depths on the same depth bins. Finally, we multiplied the mass loss, water mass concentrations, and depth-dependent thermal forcing for each water mass, giving relative contributions for basal melting for all water masses. The result for ASW and WDW is shown in Fig. R5: based on these results, ASW contributes to more basal mass loss at Fimbulisen than WDW down to 500m ice draft. Below, WDW dominates. Note that the deepest instrument (M2$_{lower}$) is located at 681m depth, restricting our estimate to this depth, but that the contribution of WDW is expected to strongly increase toward larger depths.
Following the above-described calculations, the contribution of WW to basal mass loss for the shown depth range is one to three orders of magnitude larger than the contributions of ASW and WDW. This is due to the high concentration of WW at all instruments, although the thermal forcing is smaller for WW than for ASW and WDW.

These estimates inherit many simplifications, e.g. assuming that the water mass concentrations at the instruments are valid for similar depths below the whole ice shelf. We will still look for possibilities to refine our method and will include the estimates in the revised manuscript.

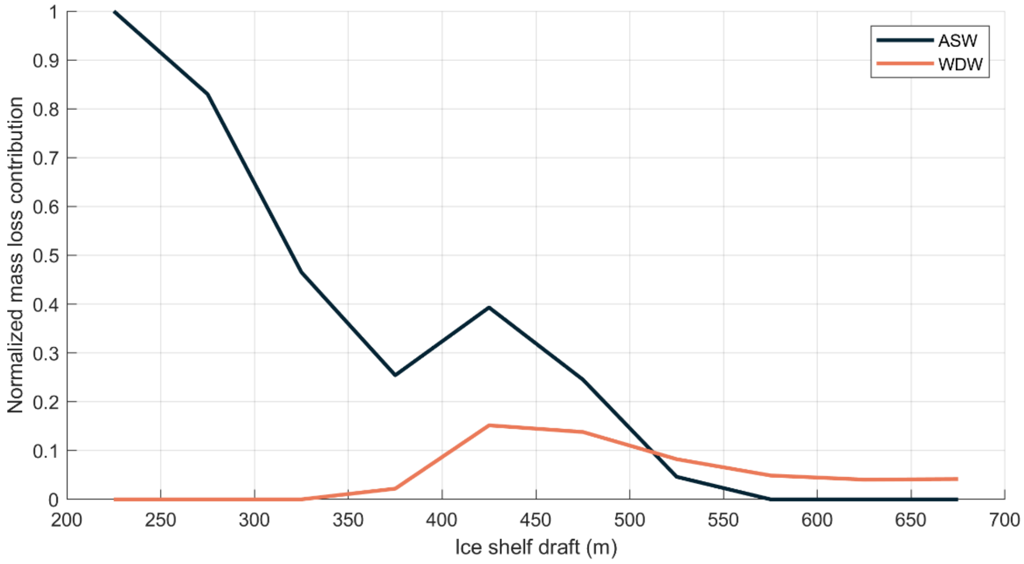

Fig. R5: Normalized mass loss contribution for ASW and WW depending on the ice shelf draft.

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