Response to reviewer R2 comments

August 22, 2025

Thank you for your detailed and helpful review. In this document, reviewer comments are in **black** and our comments are in **red**. New text added to the manuscript is in blue.

This paper discusses microstructure observations made beneath Dotson Ice Shelf using an Autonomous Submersible Vehicle. The data appear to lack the temporal and spatial coverage that would enable substantive conclusions to be drawn about the role of turbulent mixing in the larger-scale processes that operate beneath the ice shelf. They are, nevertheless, intrinsically interesting, in that they represent some of the very few direct observations that we have from within a sub-ice-shelf cavity. That remote part of the ocean plays a pivotal role in setting the mass balance of the Antarctic Ice Sheet and hence its impact on global sea level, so any observations are of value. I would therefore recommend publication of the paper with only relatively minor changes.

Thank you for your positive assessment of our manuscript. We agree that a greater spatial and temporal range of observations in ice shelf cavities is needed to gain a complete picture of the water mass transformations, heat and (fresh)water transport that influence Antarctic ice mass loss, grounding line retreat, sea level rise, deep water formation and nutrient transport. Until such measurements are routinely possible, we intend our manuscript to offer a glimpse at conditions and possible processes.

Suggested changes:

Title:

It's a minor point, but the current title does not reflect the content of the paper very well. It promises observations of ocean currents. While they are included there is very little discussion of them, and no more space is devoted to currents than to water properties.

We have changed the title of the paper to: "Observations of turbulent mixing in the Dotson Ice Shelf cavity"

Abstract:

Reflects the content of the paper and thus its main weakness, which is a lack of substantive conclusions. I accept that it is hard to put such detailed observations into a broader context, especially when they are made in such a data-poor region. However, I wonder if it might be possible to put an order of magnitude estimate on the cavity-wide mean vertical heat flux, given estimates of inflow/outflow temperatures, residence time, melt rate, etc. That would put the numbers quoted in the abstract into a useful context.

Thank you for this suggestion. We have modified our abstract to read:

"Average vertical heat fluxes are on the order of 0.1 $W\ m^{-2}$ and maximum heat fluxes reach 52 $W\ m^{-2}$. This is compared to the 59 $W\ m^{-2}$ to 176 $W\ m^{-2}$ needed to maintain observed average basal melt rates at DIS. Turbulent mixing is higher in the fast-flowing inflow region and over rough topography. We show a highly complex spatial pattern of turbulent mixing and of bottom topography. The bottom topography is currently not resolved in bathymetry products and both the topography and turbulent mixing are currently not resolved in models of ice-shelf–ocean interactions. The levels of turbulent mixing experienced by the warm mCDW inflow to the DIS will lead to negligible loss of heat during its path to the grounding line, leaving plenty of heat available to melt the ice shelf base there. Higher average vertical heat fluxes than observed here must occur in areas of the cavity not resolved in this study. ”

We have expanded on your suggestion and added the following to our results section:

“We can estimate the DIS basal melt, assuming that the entire heat flux is used to melt ice at a depth of approximately 1000 m. With this assumption the melt rate m is

$$m = \frac{Q_t}{L_i \rho_i} \tag{1}$$

with $L_i = 3.315 \times 10^5 \mathrm{J\,kg^{-1}}$ the latent heat of fusion at 1000 dbar, and $\rho_i = 917 \mathrm{kg\,m^{-3}}$ the density of ice. This results in melt rate estimates of $2 \times 10^{-3}\,\mathrm{m\,yr^{-1}}$ to $11 \times 10^{-3}\,\mathrm{m\,yr^{-1}}$. Published estimates for area averaged melt rates under DIS range from 6 1 $\mathrm{m\,yr^{-1}}$ to 18 3 $\mathrm{m\,yr^{-1}}$ (Gourmelen et al., 2017; Lilien et al., 2018; Robertson, 2013; Jenkins et al., 2018; Schodlok et al., 2012) with some estimates up to 32 9 $\mathrm{m\,yr^{-1}}$ (Jenkins et al., 2018). The low upward heat flux within the mCDW layer is thus not able to maintain the observed melt rates under DIS. To achieve the melt rate estimates from (Gourmelen et al., 2017; Lilien et al., 2018; Robertson, 2013; Schodlok et al., 2012; Jenkins et al., 2018) the vertical heat flux would need to he greater than 59 $\mathrm{W\,m^{-2}}$ to 316 $\mathrm{W\,m^{-2}}$, values three to four orders of magnitude larger than our median estimates and up to six times our maximum estimate (Table 2).

Davis et al. (2025) showed elevated levels of ε in the ice–ocean boundary layer under Thwaites, and Kimura et al. (2016) observed elevated values of ε close to the ice–ocean interface and over a bathymetric ridge in front of the PIIS grounding line. In these areas high turbulent kinetic energy dissipation rate and high vertical and horizontal temperature gradients lead to high temperature fluxes. Our study did not reach the ice–ocean boundary layer or the ridge limiting flow to the DIS grounding line (Figure 1) which may explain the underestimate of the area averaged ice shelf melt rate using the observed heat fluxes. The value for κ for stably stratifies water, used in the

ISOMIP+ protocol, matches our estimate of κ. Thus, modelled vertical heat transport, in regions for which this estimate is used, could also be too low to explain observed ice shelf melt rates. The low heat fluxes in the interior of ice shelf cavities would need to be offset by higher heat fluxes at the grounding line and in the ice–ocean boundary layer.

We can additionally estimate a melt rate for DIS from the temperature difference between the inflow and the outflow of the cavity and the average residence time of water within the cavity. We take the heat needed to warm the ice shelf to the freezing point temperature and the heat needed to warm the melt water to the temperature of the outflow into account. A back-of-the-envelope calculation for melt rate gives:

$$m = \frac{V_{in} C_p \bar{\rho} \left(\theta_{in} - \theta_{out}\right)}{\rho_i A_{DIS} \left(C_i \left(\theta_f - \theta_{ice}\right) + L_i + C_p \left(\theta_{out} - \theta_f\right)\right)} \qquad (2)$$

with $V_{in} = v_{cavity} A_{inflow}$, the volume transport in the inflow; $v_{cavity} = \frac{D}{t}$ the velocity of the inflow; D the distance water has to travel from the ice front to the grounding line and back; t the time the water takes to travel to the grounding line and back; A_{inflow} the area through which water flows into the cavity; A_{DIS} the area of the DIS; C_i the specific heat capacity of ice at $-2\,°\mathrm{C}$ and 1000 db; θ_f the freezing point temperature of seawater; θ_{in} the average temperature of the inflow to DIS; θ_{out} the average temperature of the outflow from DIS; θ_{ice} the far-field internal temperature of the DIS.

We assume the following values for these parameters: D =240 km (Figure 1); t =2 months (Milillo et al., 2022; Yang et al., 2022; Girton et al., 2019); $A_{inflow} = 500\,\mathrm{m} \times 15\,\mathrm{km}$ (solid box in Figure 3); $A_{DIS} = 5200\,\mathrm{km}^2$ (Lilien et al., 2018); $\theta_f \approx -2\,°\mathrm{C}$; $\theta_{in} = 0\;2\,°\mathrm{C}$ (the average temperature in the solid box in Figure 3); $\theta_{out} = 0\;17\,°\mathrm{C}$ (the average temperature in the dashed box in Figure 3, the outflow extends to shallower depths in the water column than the inflow due to the thinner ice shelf draft in the west of the DIS (e.g. A. Wåhlin et al., 2024).); $\theta_{ice} = -25\,°\mathrm{C}$, an estimate of the far-field ice temperature. Our estimate of melt rate and heat flux from in and outflow temperatures is most sensitive to the area over which we average outflow temperatures (Figure 3) and represents an order of magnitude estimate only.

Equation 2 results in an estimate of the melt rate of $\sim 10 \pm 5\,\mathrm{m\,yr^{-1}}$, which lies within the range of published values (e.g. Gourmelen et al., 2017; Lilien et al., 2018; Robertson, 2013; Schodlok et al., 2012; Jenkins et al., 2018). To maintain this melt rate the vertical heat flux in the cavity would need to be $100 \pm 50\,\mathrm{W\,m^{-2}}$, about three orders of magnitude higher than the median values along the east dive track (Table 2). Rearranging Equation 2 allows us to estimate the percentage of the heat entering the ice shelf cavity that is used to melt ice. We estimate that the inflow transports $4 \pm 2\,\mathrm{TW}$ into the cavity and the melt takes up $0\,6 \pm 0\,4\,\mathrm{TW}$, thus, only $\sim 15 \pm 9\,\%$ of the heat entering DIS is used to melt the ice shelf. Modelling studies have estimated this value to be smaller, at 8 % (Jourdain et al., 2017), but within our error range. Transport calculations by Jenkins et al. (2018) yield the same range for heat flux into the cavity as our estimate does, however, their calculated melt rate, derived from melt water fluxes, is significantly higher ($6\,\mathrm{m\,yr^{-1}}$ – $33\,\mathrm{m\,yr^{-1}}$). These melt rates would require heat fluxes of $60\,\mathrm{W\,m^{-2}}$ – $317\,\mathrm{W\,m^{-2}}$. We need significantly more measurements under ice shelves to understand the role of mixing in different areas and regimes, and its effect on ice shelf melt rate."

Introduction:

The first paragraph talks about the DIS contribution to Amundsen Sea "mass loss", suggesting that the term refers to shrinkage of the ice sheet. However, the latter part of the paragraph partitions "mass loss" for the ice shelves between calving and melting. In this instance the term does not refer to shrinkage of the ice shelves, but the contribution to the wastage side of the mass budget. Those are different concepts, and the distinction should be clarified.

Thank you for pointing out this ambiguity, we have rephrased this paragraph to now only refer to ice sheet mass loss and basal melt/thinning of the ice shelf. The revised paragraph now reads "Between 1979 and 2017 DIS contributed 0 6 mm to global eustatic sea level rise (Rignot et al., 2019). The rate of discharge across its grounding line has increased throughout the satellite record (Rignot et al., 2019; Mouginot et al., 2014) and the grounding line has retreated (Rignot et al., 2014; Scheuchl et al., 2016; Milillo et al., 2022). The increased ice flux across the Dotson grounding line, coupled with the stable ice flux across the calving front (Rignot et al., 2013; Mouginot et al., 2014) and the increased thinning of the ice shelf (Rignot et al., 2013; Mouginot et al., 2014; Gourmelen et al., 2017; Greene et al., 2022) leads to the conclusion that ocean thermal forcing has increased basal melt of the ice shelf (e.g. Mouginot et al., 2014). Dotson has thinned at a 37% higher rate than the average rate of thinning in the Amundsen Sea (Paolo et al., 2015). "

The last paragraph states that there have been only two previous published studies of mixing beneath ice shelves, but that overlooks studies based on borehole data. The oversight is repeated in other parts of the manuscript.

This is a good point. We clarify the Introduction, by referring to autonomous vehicles: "To our knowledge, there exist two published studies of mixing in an ice-shelf cavity measured by an underwater vehicle, one under Pine Island Glacier (Kimura et al., 2016), and one under the Filchner Ronne Ice Shelf (Davis et al., 2022). We present a third such study, targeting DIS." and discuss comparisons with borehole results in the Discussion section. To our knowledge there are three published studies of successful measurements of mixing through ice shelf boreholes in the Antarctic (Davis & Nicholls, 2019; Venables et al., 2014; Davis et al., 2025), but if you are aware of others we have missed, we would happily include them. We have added the new Figure 8 and the following paragraph to the revised manuscript:

"The highest levels of turbulent mixing occur in the inflow region at the ice front and in the east dive track, decreasing into the cavity (Figure 5 and Figure 6). The east dive track clearly shows the highest values for ε of the three ALR dive tracks at DIS (Figure 8). The range, maximum and median values of ε measured with the VMP at the ice front are higher than those observed in the cavity with the ALR, but ranges have a wide overlap.

We compare our observations of turbulent kinetic energy dissipation rate with other observations under Ronne Ice Shelf (measured using a MicroRider mounted on an ALR; Davis et al., 2022), George VI Ice Shelf (measured with a VMP through a borehole; Venables et al., 2014), Thwaites Ice Shelf (measured with a VMP through a borehole; Davis et al., 2025) and Larsen C ice shelf (measured with a turbulence instrument cluster moored close to the ice–ocean interface; Davis & Nicholls, 2019). The distributions of ε under Ronne and George VI have similar shapes and ranges to our observations (Figure 8). The VMP observations do, however, show much higher maximum values. This is likely caused by the greater vertical extent of the VMP measurements, which reach into the ice–ocean boundary layer where ε is elevated (Davis et al., 2025). This is confirmed by the measurements 2.5 m and 13.5 m from ice-ocean interface under Larsen C, which show the highest average values of ε of the measurements included in Figure 8. Further studies are needed to establish whether observed differences between ice shelves are driven by different mixing regimes or different observation techniques. The current state of knowledge leads us to conclude that the measurements taken under Dotson agree remarkably well with available distributions of ε from other ice shelves, outside of the ice–ocean boundary layer. ”

Data and methods:

On line 127 there is a parenthetical note to authors that has not been addressed.

We are very sorry to have missed that! Thank you for pointing it out, the note has been removed.

On line 140 the dimensionless parameter could more precisely be referred to as a “gradient Richardson number”.

Yes, we will make that change.

On line 165 there is a mention of detiding LADCP data using CATS2008. Elsewhere it is stated that tides are unimportant, and CATS cannot be trusted because of the poor bathymetry in the model. One comment refers to (mainly) sub-ice data and the other to ice front data, but nevertheless the treatment seems inconsistent. If bathymetry is poor beneath the ice, won't that influence currents at the ice front? If tides are weak enough to be ignored, why bother with detiding the LADCP data?

Thank you, we acknowledge that this is confusing for readers and have rephrased the text to make this clearer.

- As noted by the reviewer, the bathymetry is worse in the cavity than outside it due to a lack of observations in the cavity (as shown in Figure 7), which is why we trust the CATS2008 model more at the ice front than in the cavity.
- At the ice front section we have ship ADCP for validation of the CATS model, making us more confident in the tide model solution for correcting the LADCP.
- The tidal currents at the ice front are indeed small O(1 cms^{-1}) (Dotto et al., 2025).
- We expect the effect of tides in the cavity to be influenced by the barotropic jump at the ice front, something not well captured in the CATS model.
- We could not identify a tidal signal in our ALR ADCP time series in the cavity and thus we concluded that the error introduced by a faulty tidal model would likely be larger that the error caused by not detiding.
- On a practical point, the LADCP data were processed and detided by Dotto et al. (2025), and in order to stay consistent with Dotto et al. (2025) we use their detided dataset (Dotto, Tiago S et al., 2024) in our study.

We make these methodological approaches clearer in the revised paper. The relevant section of the methods now reads:

"Upward-looking and downward-looking LADCP measurements were processed with the LDEO_IX toolbox, incorporating information from the vessel-mounted ADCP, CTD, GPS and bottom track from the LADCP (Thurnherr, 2021). The processed data were averaged into 8-m vertical bins and detided using an updated version of the CATS2008 Antarctic tide model (Padman et al., 2002; Erofeeva et al., 2024). Modelled tidal current components are on the order of $1\,\mathrm{cm\,s^{-1}}$ at the ice front and the tide model agrees well with tides extracted from the shipboard ADCP data (Dotto et al., 2025). Conversely, the ALR ADCP data are not detided due to the ill-constrained bathymetry under DIS, the absence of a detectable tidal signal in a spectral analysis of the ALR ADCP currents in the cavity, and the risk of degrading the ADCP data quality with an ill-fitting tidal model. "

Results and discussion:

In the title of section 3.1 and elsewhere in the manuscript the edge of the ice shelf is referred to as the "ice shelf front". The correct term for that feature is the "ice front".

We have made this change.

In figure 3, is there a "black line" showing the track of the ALR (third line of the caption)? I couldn't see one.

Thank you for this feedback, we have removed the line (which is obscured in large parts by the coloured dots showing the ALR measurements along the track.) and the reference to it from the figure caption.

On lines 222-223 it is stated that water at the ice front is colder and lighter than that in the cavity. Does that refer only to measurements made with ALR? Was the warmer, saltier water apparent in the section observed with the ship? If not, I think it deserves some comment about where that warm, salty water may have come from? Waters in the cavity must be cooled and freshened, so the observation must say something about variability at the ice front. If, on the other hand, an equally warm, salty water mass is present in the ship CTD data, then the statement in the paper is a little misleading.

The statement on lines 222–223 refers to the ship CTD section along the ice front. We have made this clearer in the revised paper. The revised paragraph reads:

"Water at the ice front (measured with the ALR and the ship CTD) is colder but lighter than water found deeper in the cavity (Figure 6). The temperature (Figures 6 and 5) and salinity (not shown) in the cavity generally increase with depth. The presence of warmer, saltier, and denser water in the cavity than at the ice front may indicate seasonal or interannual variability in the properties of the water at the ice front (as described by Kim et al. (2021)) and thus of water flowing into the cavity."

On lines 228-229, and elsewhere, it is stated that the observations reported in the paper are important for establishing mixing rates that can be "incorporated into numerical models". It is not clear to me how these data would be incorporated into a model. Perhaps the point could be clarified?

Thank you, we are happy to expand and clarify how our results may inform modelling efforts. We have removed the reference to parameterisations in lines 228–229 and adding the following to the manuscript at the end of section 3.2: "Maximum and median values of diapycnal diffusivity κ, vertical heat flux Q_T, and vertical salt flux Q_S from our observations under DIS are given in Table 2. Our median values of diapycnal diffusivity ($O(10^{-4}\,m^2\,s^{-1}$–$O(10^{-5}\,m^2\,s^{-1}$)) are the same order of magnitude as globally-averaged ocean values (Waterhouse et al., 2014). The maximum values of diapycnal diffusivity in our study ($O(10^{-2}\,m^2\,s^{-1}$–$O(10^{-3}\,m^2\,s^{-1}$)) match values observed close to the seabed over rough terrain or at ridges (Waterhouse et al., 2014).

Our observations under DIS provide valuable metrics against which turbulent mixing processes in numerical models could be assessed. Turbulent kinetic energy dissipation dissipation is not modelled or parameterised in regional or global models. Instead, diapycnal diffusivity κ is parametrised. A common parametrisation of diapycnal diffusivity in ice shelf cavities is the vertical profile method from Large et al. (1994) (e.g. in ROMS; Gwyther et al. (2015) or MITgcm; Nakayama et al. (2017)) which assumes higher values of κ in boundary layers than in the interior. The interior mixing is made up of contributions from internal waves (parameterised as a constant), from shear instability (parameterised from the gradient Richardson number), and from double diffusion (parameterised from the double diffusion density ratio) (Large et al., 1994). The ice base roughness has been shown to influence the ice–ocean boundary layer mixing and the heat and salt flux into the boundary layer, and thus the spatial and temporal distribution of ice shelf melt (Gwyther et al., 2015). We are not aware of studies investigating the effects of spatially variable bottom boundary layer roughness on mixing and basal melt in an ice shelf cavity. The range of values for κ, the spatial variability, and forcing mechanisms we discuss, can be compared to the values and variability of the κ profile parametrisation. This may allow a better understanding of the contribution of different drivers to mixing and of how realistic model mixing is.

Another common choice to parametrize mixing, used in the ISOMIP+ protocol (Asay-Davis et al., 2016), is to prescribe constant values for κ in the vertical and horizontal, with higher values where the water column stratification is unstable. In stably stratified water, as under DIS, the ISOMIP+ protocol sets as $\kappa_{v,stable} = 5 \times 10^{-5} m^2 s^{-1}$ (Asay-Davis et al., 2016). The value of κ used in ISOMIP+ has the same order of magnitude as the median value in the centre_short dive track ($2 \times 10^{-5} m^2 s^{-1}$), but is an order of magnitude lower than the median κ on the east dive track ($1.1 \times 10^{-4} m^2 s^{-1}$) and 2–3 orders of magnitude lower than the maximum values we find within the cavity (Table 2). Thus, the constant value of κ used in ISOMIP+ is a good choice for slow flows with low shear over smooth topography, but may underestimate mixing in other areas which may in turn influence modelled ice-shelf melt. "

On line 230, mention is made of a 100 m thick "melt layer" observed through a borehole. What feature are you referring to? The upper 100 m of the borehole data shown in Figure 2 appear to indicate the presence of less meltwater than deeper in the water column. Why is that? A shallow intrusion of WW along the ice shelf base?

You are correct that this water may show a shallow intrusion of WW, we have removed the reference to a melt layer.

Lines 197-203 draw comparisons with observations made at Pine Island Ice Front but point out differences in the physical setting. One difference that might be relevant, but which appears to have been overlooked, is that in the case of Pine Island there is a neighboring ice shelf to the north, so the northern sidewall of the channel confining the Pine Island Ice Shelf does not extend all the way to the ice front.

Thank you for pointing this out, we have changed the relevant paragraph in the revised manuscript to reads: “At the nearby Pine Island Ice Shelf (PIIS) Naveira Garabato et al. (2017) conducted ADCP and VMP transects along the calving front. Naveira Garabato et al. (2017) do not detect a fast, narrow, turbulent inflow current, unlike what we observed at DIS (Figure 3). High rates of turbulent kinetic energy dissipation below the WW were mostly confined to the PIIS outflow. The PIIS is connected to another ice shelf cavity to the north and may receive some of its inflow from under this neighbouring ice shelf, which may decrease the inflow across the PIIS front and possibly the turbulent mixing there. Additionally, the ice shelf draft of the PIIS is deeper ($\approx 400\,\mathrm{m}$) than the DIS ($\approx 350\,\mathrm{m}$). The ice shelf draft induces a barotropic jump (an abrupt change in water column thickness, blocking flow along constant lines of water column thickness) and limits barotropic inflow to the cavity (A. K. Wåhlin et al., 2020), thus decreasing inflow current velocities and possibly turbulent mixing. ”

The last four paragraphs compare findings with other AUV based observations of microstructure beneath ice shelves. However, elsewhere the manuscript highlights the differences between those regions. That makes the discussion feel like one that is motivated by common methodology rather than common physical setting. Why overlook borehole measurements of turbulence that have been made within cavities? Later in the section it is suggested that the

AUV track beneath FRIS is 9 km long, but that does not seem to fit with the figures in the cited paper. At the end the of the section the text again talks about improving parameterisations of mixing in models, but again, I don't really see how you would use the data for that.

Yes, these are good points, thank you for the suggestions. We have strengthened the discussion by adding comparisons with borehole data to the revised manuscript, we have given details on the revised text above. Apologies for the incorrect length of the FRIS dive track, this has been corrected. We have expanded our argument on how our observations can be used to inform modelling studies, the relevant text is included above.

Lines 334-335 suggest that the small vertical heat flux observed means that a lot of ocean heat can be used to melt ice at the grounding line. But how much is used there? The outflows at the ice front remain above the freezing point, so some ocean heat that enters the cavity exits it without being used for melting. Again, can you estimate some global budgets for the amount of heat used for melting and the overall average vertical heat flux that could put your spatially-limited observations in a DIS-cavity-relevant context?

These are good suggestions. We have added an estimation of the heat flux in DIS to the revised manuscript. The paragraph reads: "Equation 2 results in an estimate of the melt rate of $\sim 10 \pm 5\,\mathrm{m\,yr^{-1}}$, which lies within the range of published values (e.g. Gourmelen et al., 2017; Lilien et al., 2018; Robertson, 2013; Schodlok et al., 2012; Jenkins et al., 2018). To maintain this melt rate the vertical heat flux in the cavity would need to be $100 \pm 50\,\mathrm{W\,m^{-2}}$, about three orders of magnitude higher than the median values along the east dive track (Table 2). Rearranging Equation 2 allows us to estimate the percentage of the heat entering the ice shelf cavity that is used to melt ice. We estimate that the inflow transports $4 \pm 2\,\mathrm{TW}$ into the cavity and the melt takes up $0\,6 \pm 0\,4\,\mathrm{TW}$, thus, only $\sim 15 \pm 9\,\%$ of the heat entering DIS is used to melt the ice shelf. Modelling studies have estimated this value to be smaller, at 8 % (Jourdain et al., 2017), but within our error range. Transport calculations by Jenkins et al. (2018) yield the same range for heat flux into the cavity as our estimate does, however, their calculated melt rate, derived from melt water fluxes, is significantly higher ($6\,\mathrm{m\,yr^{-1}} - 33\,\mathrm{m\,yr^{-1}}$). These melt rates would require heat fluxes of $60\,\mathrm{W\,m^{-2}} - 317\,\mathrm{W\,m^{-2}}$. We need significantly more measurements under ice shelves to understand the role of mixing in different areas and regimes, and its effect on ice shelf melt rate. "

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