Review:

Egusphere-2024-3513: Stratified suppression of turbulence in an ice shelf basal melt parameterisation

Overall Statement:

The submitted manuscript targets a very important goal, to improve parameterized melt rates over a range of oceanographic forcings in regional-scale ice shelf-ocean models. This is certainly a worthwhile study that will eventually produce a meaningful contribution to the cryosphere science community. The present manuscript draft starts out fairly strong, but becomes cluttered and hard to follow as it progresses, making the Results Section actually quite hard to interpret based on which methodological approach was taken. There are also some holes in the approach that I have outlined as areas of improvement. While I do not believe that all of these suggested comments need to be implemented, the authors should really consider them and at least add caveats to the text for transparency. The suggested changes will constitute a major revision, but I do believe that this study worthy of eventual publication and will make a nice contribution to the cryosphere science community.

Larger Comments:

The Introduction is quite good, but lacks some qualification on the effects of realistic small-scale slopes on ice shelf basal melting around Antarctica. Please add several sentences that play this out some. This could include some discussion of the very interesting variation in melt in a terrace, for instance.

Need to define the regions of the boundary layer in the Introduction, as there are parts of the Methodology that are unclear to the reader as to which part of the boundary layer the authors are referring to.

Methodology says very little about salinity differences, which are the key driver of stratification in the boundary layer in a warm cavity ice shelf.

Introduction should state the velocity ranges considered here before discussing friction velocity.

Consider boiling down the parameterization results to Stanton Numbers and constant Gammas, so that larger-scale models and observations that do not resolve all the way up to the ice base can implement these results into something easily useable.

Authors generally do not seek to ground their modeling in observations of the highly varied and sloping bases of Antarctica’s ice shelves.

I think the authors have a real opportunity here to implement the StratFeedback+MK18 parameterization in the MITGCM Pine Island Glacier model run to take into account the external shear-driven turbulence, near-ice stratification, and the destabilizing effect rising meltwater on sloping ice bases. This will really round out the study and should test the influence of external turbulence plus localized rising plumes in a significant manner.

Generally, the Results Sections are hard to interpret, because it is hard for the reader to disentangle the details of which Methodology was used for each section.

Specific Revisions:

Abstract:

This is a long abstract that Microsoft Word registers as 257 words. Please double check that this fits within the journal's word count limit.

Li 7: "and diffusive convection plays a role…" This is an unfinished statement. Please rewrite to finish this thought.

Li 11 – 15: This section focuses on the suppression of melt by stratification, but does not mention the effects of diffusive convection, which is mentioned previously. Rewrite this section to add some discussion of diffusive convection.

Introduction:

Li 23: It would be helpful to add a more recent citation here on recent acceleration in melting; the latest one was over a decade ago in 2014.

Li 32: While not from Antarctica, this study is very applicable to stratified ocean-driven melt of ice shelves and could be added to this list: (Washam et al., 2020). It also has to do with buoyancy-driven circulation and melt, so probably fits into the introduction well.

Washam, P., Nicholls, K. W., Münchow, A., & Padman, L. (2020). Tidal modulation of buoyant flow and basal melt beneath Petermann Gletscher Ice Shelf, Greenland. *Journal of Geophysical Research: Oceans*, *125*(10), e2020JC016427.

Li 39: I suggest to change to "the variable molecular diffusion of heat and salt"

Li 46: Should this be "turbulent mixing and heat **and salt** transport"

Li 50 – 54: I think somewhere in this part of the introduction or before it should be mentioned that "buoyancy-driven convection" only enhances melt along sloping ice bases, and that the growing number of observations from beneath ice shelves show that their bases' are quite rough with many slopes.

Li 70: Please add one or both of the following citation to the statement that variation in melt rate within each ice shelf is significant: (Vaňková and Nicholls, 2022; Vaňková et al., 2023).

Vaňková, I., & Nicholls, K. W. (2022). Ocean variability beneath the Filchner-Ronne ice shelf inferred from basal melt rate time series. *Journal of Geophysical Research: Oceans*, *127*(10), e2022JC018879.

Vaňková, I., Winberry, J. P., Cook, S., Nicholls, K. W., Greene, C. A., & Galton-Fenzi, B. K. (2023). High spatial melt rate variability near the Totten Glacier grounding zone explained by new bathymetry inversion. *Geophysical Research Letters*, *50*(10), e2023GL102960.

Li 87: This statement is way oversimplified and should be removed: "whereas Antarctic ice shelves are generally weakly sloped (<1°)". There are a growing number of observations that show this is not the case over many scales, from scalloped morphology (<1 m) to a several km grounding zone.

Melt Parameterisation Design and Validation:
The Three-Equation Melt Paramterisation and Transfer Coefficients

Li 127: I would say the ice-ocean boundary temperature is also a key unknown, but if you solve the three equations T_b and S_b will drop out through the quadratic expression. Perhaps you can add some discussion on this to this section, which is typically glossed over in papers. This could also be added to the Li 132.

Li 140: Also an opportunity to cite the Washam et al. (2020) paper.

Li 146 – 151: Again, this is focused on flat portions of the ice shelf and requires a qualifying statement that sloped ice can melt faster that the J10 and HJ99-M81 parameterizations, e.g., Schmidt et al., (2023).

Li 148: I think it would be helpful to add the M81 stability parameter as an equation, so that the reader can be compare it with (5) in the following discussions. I do see it later in the Appendix, but it may help to have it in the main body or at least reference that it is in the Appendix.

Li 151 – 160: Please include a discussion of Washam et al., (2023) and Lawrence et al., (2023) in this section on drag coefficients, as both studies quantified ice shelf morphology and related them to a u_* and C_D from observations.

Washam, P., Lawrence, J. D., Stevens, C. L., Hulbe, C. L., Horgan, H. J., Robinson, N. J., ... & Schmidt, B. E. (2023). Direct observations of melting, freezing, and ocean circulation in an ice shelf basal crevasse. *Science Advances*, *9*(43), eadi7638.

Lawrence, J. D., Washam, P. M., Stevens, C., Hulbe, C., Horgan, H. J., Dunbar, G., ... & Schmidt, B. E. (2023). Crevasse refreezing and signatures of retreat observed at Kamb Ice Stream grounding zone. *Nature Geoscience*, *16*(3), 238-243.

Stratification Feedback on Turbulence – Insights from Large Eddy Simulations:

Li 161 – 167: This paragraph never mentions salinity, which is the principle driver of density at the ocean temperatures responsible for melting ice shelves. Please properly attribute stratification to difference in density, driven by salinity changes. Additionally, and potentially more important, this discussion only applies to flat or gently-sloping ice where meltwater pools instead of rises vigorously to act as a source of turbulence that destratifies the boundary layer. This must be said in this paragraph also.

Li 173: Does a small L^+ here refer to an absolute sense or a highly negative value? This is slightly non-intuitive, since there is a negative in front of u_* in (5), g is a positive 9.80 m/s2, and one might expect $T_b - T_M$ to be larger (more negative) than $S_b - S_M$, which would result in a positive buoyancy flux. Please spell this out for the reader, or preferably, move the expressions around in the 3 equation parameterization to place a positive sign in front of the heat/salt flux and make it $T_M - T_b$ ($S_M - S_b$), then place a negative sign in front of the heat conduction into the ice shelf.

Li 173: Is this kinematic viscosity or eddy viscosity?

Li 189 – 190: I do not understand how the cooling effect of melting is not accounted for in L^+, since the buoyancy term (B_b) should exhibit some change in T_M and S_M as the boundary layer cools and freshens from melting. Unless T_M and S_M are chosen at a sufficient distance to be truly "far-field." To be honest, I have a hard time understanding where T_M and S_M are chosen in most papers. Please elucidate this more clearly in this section.

Stratification Feedback Parameterisation Design:

Li 194: Add "along flat or gently-sloping ice to the end of this sentence."

Li 205 – 207: Briefly comment on how neglecting the heat conductive flux will influence results, citing literature that has considered this variable, e.g., Arzeno et al. (2014), Washam et al. (2020), and others. Note that importantly at low ocean heat fluxes, the conductive heat flux through the ice shelf can be nearly as high as the ocean heat flux, which plays an important role in transitioning from melting to freezing.

Arzeno, I. B., Beardsley, R. C., Limeburner, R., Owens, B., Padman, L., Springer, S. R., ... & Williams, M. J. (2014). Ocean variability contributing to basal melt rate near the ice front of Ross Ice Shelf, Antarctica. *Journal of Geophysical Research: Oceans*, *119*(7), 4214-4233.

Li 211 – 212: The velocity in the boundary layer should be less than far-field, because the oceanic flow is starting to feel the friction of the ice base, which generates turbulent eddies that mix heat and salt towards the ice. There are also multiple regions of the boundary layer, such as the outer, surface, and viscous sublayer, that have not been properly defined at this point (see general comment). All of this needs to be spelled out clearly to the reader, and sentences like this are presently confusing, because the boundary layer has not been properly introduced.

Li 216 – 217: If the whole domain is laminar, then there is no turbulence, right? Then if the drag coefficient is related to the friction velocity and therefore turbulence, how can there be a drag coefficient if there is no turbulence? I realize that this is a literature review, but I think this should be presented more clearly to the reader.

Li 221: Please change to vary the thermal and haline Stanton numbers (\Gamma_T((C_D)^{1/2}) and \Gamma_T((C_D)^{1/2}))

Li 223 – 228: This sentence suggests that the authors are solving the two-equation parametrization, where there is a salinity difference across the boundary layer of 0. I don't think this is actually the case, but it would be helpful for the authors to clarify this in the text.

Li 223 – 239: I believe that it is roughly an order of magnitude greater, but it would be helpful to just state the actual far-field velocity range that could produce u_* values of 0 – 0.010 m/s.

Comparison to Observations:

Li 241 – 260: See comment on Figure 3 below also. Please add Ross Ice Shelf data from Washam et al. (2023) to these plots. While not Antarctica, it may also be helpful to place the detailed data from Petermann Glacier into this discussion.

Washam, P., Lawrence, J. D., Stevens, C. L., Hulbe, C. L., Horgan, H. J., Robinson, N. J., ... & Schmidt, B. E. (2023). Direct observations of melting, freezing, and ocean circulation in an ice shelf basal crevasse. *Science Advances*, *9*(43), eadi7638.

Washam, P., Nicholls, K. W., Münchow, A., & Padman, L. (2020). Tidal modulation of buoyant flow and basal melt beneath Petermann Gletscher Ice Shelf, Greenland. *Journal of Geophysical Research: Oceans*, *125*(10), e2020JC016427.

Li 248: I would be careful to say that ignoring heat conduction makes no difference on melt rate parameterization at low ocean heat and salt fluxes, i.e., cold cavity conditions.

Limiting to a Velocity-Independent Parameterisation:

Li 266: Following the comment above, it would be helpful to define what velocity range constitutes "low-velocity."

Li 274 – 275: Thank you for identifying the varying ocean-forced mechanism that relate to differing ice slopes.

Li 299: turbulent or molecular diffusion? If molecular, then the sublayer thickness will need to be accounted for and the temperature and salinity gradient across it. If turbulent, please explain this further. Is it just a really low U multiplied by sqrt(C_D)?

Li 266 – 306: I see no discussion of a combined StratFeedback+MK18 in this section, but (I think) this is most likely what happens in the real world along sloping ice shelf bases and I see it in Figure 2. I suggest to add a few sentences that discuss this parameterization to this section.

Model Configurations

ISOMIP+ Setup and Modifications

Li 324 – 325: I do not think that the cold cavity setup is restored to a very realistic T/S profile. It is fine to take a full isothermal temperature profile to represent deep convection, but if that is the case, then the salinity profile should also be nearly uniform. In any case, the choice of a surface salinity of 33.8 g/kg seems too fresh if all the freshening is to be accounted from ice melt. Take a look at hydrographic sections in front of the Ross and Filchner-Ronne and adjust accordingly. It doesn't have to be perfect, but I suggest a lower salinity range.

Li 329: Please consider adding in the heat conduction term to these models, as it will become important in the cold cavity, low heat/salt flux scenarios, especially when the ice draft is thin. If this is not possible, remark on this as a weakness of this experiment and discuss the caveats.

Idealised MOM6 Configuration

LI 335 – 349: Please explicitly mention the uppermost layer vertical grid cell size range here and remark on how well it represents observations of the boundary layer beneath ice shelves.

Idealised MITgcm Configuration

Li 351 – 3558: Similarly, remark on whether the 5 m partial grid cell can adequately resolve the boundary layer.

Idealised Explicit Tidal Forcing:

Li 360 – 372: Do these tides pass the critical M2 latitude in your simulations? Is this included?

Li 370 – 372: Do these decreased tidal velocities represent observations, e.g., Jenkins et al. (2010) or Davis & Nicholls (2019)? I don't think so. Please remark on why this is the case.

Pine Island Glacier Configuration:

Li 388 – Li 390: I highly recommend adding in the StratFeedback+MK18 parameterization to this study, as you are now dealing with a (somewhat) realistic model configuration that will experience external shear-driven turbulence, stratification, and rising meltwater plumes. This would really take this study over the top!

Results:

Idealised ISOMIP+ Results:

Li 396 – 398: Add a similar discussion on salinity differences, which are the primary driver of stratification (last time I say this), and see comment below on Figure 4.

Li 408 – 414: Perhaps this can wait until the Discussion Section, but I think L^+ could be artificially low in these simulations, because of the course grid size. Consider adding a section that explicitly discusses how vertical resolution affects L^+ and compare it to either high resolution model runs or observations to properly ground these results.

Li 429: Suggest to not cite manuscripts in preparation.

Sensitivity to the Low-Velocity Limit:

431: Wait, were tides included in all of the results from the previous section? If so, it was not clear to the reader, so please restate it in that section. Later in Li 439 I see that it is fully thermohaline. Please make this clearer.

Energetic Ice Shelf Cavity Regimes:

Li 460 – 491: This section should evolve after the appropriateness of L^+ in these simulations has been assessed following the prior comment (Li 408 - 414). Or, this can wait to the discussion section.

Realistic Pine Island Glacier Simulation:

Li 493 – 532: I highly suggest to also implement the StratFeedback+MK18 parameterization into this analysis, i.e., a parameterization that includes the influence of ice base slope, stratification, and external turbulence.

Li 521 – 524: If I understand this right, this was hardly a 'tuning' of the drag coefficient and more of picking a single observed drag coefficient and applying it to the whole model. At this point it is quite difficult to follow what method has been used where. Regardless, I would not refer to this as a 'tuning,' but instead an 'altering' of the drag coefficient, then please state explicitly in this section what C_D was changed from and to. I also took a look back at the Stanton et al. (2013) paper and don't see a value for C_D, but instead only a timeseries of u_* without any mention of U. How as C_D computed then? Another approach to this problem would be to use the range of C_D values observed beneath ice shelves and force the model with each of them to see how it influences the melt rates.

Discussion:

Li 534 – 572: All of this reads more like a Summary than a Discussion and should be rewritten to provide more helpful analysis of the results.

Li 573 – 585: Ok, this somewhat satisfies my prior comments on the validity of L^+ in these simulations, but given (what I think is) the goal of this study to more accurately parameterize melt rates, I think this section should be expanded to include model-obs comparisons or coarse-fine model comparisons.

Figures:

Figure 1d: Consider adding lines for C_D from more observations beneath ice shelves, such as Jenkins et al. (2010), Davis and Nicholls (2019), Washam et al. (2023), and Lawrence et al. (2023).

Figure 2b: Consider adding a range of ice base angles (4 or 5 angles between 10° and 90°) to this figure or to the Appendix, since 10° seems to be somewhat arbitrary and low, without any real acknowledgement of the many small-scale slopes observed beneath ice shelves, e.g., Dutrieux et al. (2014), Schmidt et al. (2023), Lawence et al. (2023), Washam et al. (2023), etc…

Dutrieux, P., Stewart, C., Jenkins, A., Nicholls, K. W., Corr, H. F., Rignot, E., & Steffen, K. (2014). Basal terraces on melting ice shelves. *Geophysical Research Letters*, *41*(15), 5506-5513.

Figure 3: Please add Ross Ice Shelf data from Washam et al. (2023) to these plots. While not Antarctica, it may also be helpful to place the detailed data from Petermann Glacier into this figure.

Washam, P., Lawrence, J. D., Stevens, C. L., Hulbe, C. L., Horgan, H. J., Robinson, N. J., ... & Schmidt, B. E. (2023). Direct observations of melting, freezing, and ocean circulation in an ice shelf basal crevasse. *Science Advances*, *9*(43), eadi7638.

Washam, P., Nicholls, K. W., Münchow, A., & Padman, L. (2020). Tidal modulation of buoyant flow and basal melt beneath Petermann Gletscher Ice Shelf, Greenland. *Journal of Geophysical Research: Oceans*, *125*(10), e2020JC016427.

Figure 4: I suggest to add two rows that are similar to a-h, but present Salinity.

Figure 7: Given that there have been scalebar changes in the comparison of cold and warm cavities in Fig 4 and 6, I suggest to change the vertical axis in panel **b** and use lower melt rate contour lines to make it more useful. Simply state once again to note the scale change.

References:

Arzeno, I. B., Beardsley, R. C., Limeburner, R., Owens, B., Padman, L., Springer, S. R., ... & Williams, M. J. (2014). Ocean variability contributing to basal melt rate near the ice front of Ross Ice Shelf, Antarctica. *Journal of Geophysical Research: Oceans*, *119*(7), 4214-4233.

Dutrieux, P., Stewart, C., Jenkins, A., Nicholls, K. W., Corr, H. F., Rignot, E., & Steffen, K. (2014). Basal terraces on melting ice shelves. *Geophysical Research Letters*, *41*(15), 5506-5513.

Lawrence, J. D., Washam, P. M., Stevens, C., Hulbe, C., Horgan, H. J., Dunbar, G., ... & Schmidt, B. E. (2023). Crevasse refreezing and signatures of retreat observed at Kamb Ice Stream grounding zone. *Nature Geoscience*, *16*(3), 238-243.

Vaňková, I., & Nicholls, K. W. (2022). Ocean variability beneath the Filchner-Ronne ice shelf inferred from basal melt rate time series. *Journal of Geophysical Research: Oceans*, *127*(10), e2022JC018879.

Vaňková, I., Winberry, J. P., Cook, S., Nicholls, K. W., Greene, C. A., & Galton-Fenzi, B. K. (2023). High spatial melt rate variability near the Totten Glacier grounding zone explained by new bathymetry inversion. *Geophysical Research Letters*, *50*(10), e2023GL102960.

Washam, P., Nicholls, K. W., Münchow, A., & Padman, L. (2020). Tidal modulation of buoyant flow and basal melt beneath Petermann Gletscher Ice Shelf, Greenland. *Journal of Geophysical Research: Oceans*, *125*(10), e2020JC016427.

Washam, P., Lawrence, J. D., Stevens, C. L., Hulbe, C. L., Horgan, H. J., Robinson, N. J., ... & Schmidt, B. E. (2023). Direct observations of melting, freezing, and ocean circulation in an ice shelf basal crevasse. *Science Advances*, *9*(43), eadi7638.