Response to comments

We wish to thank anonymous reviewer for their valuable comments, which will help us to improve our manuscript. We addressed each of the comments in turn below. Our responses are colored by green.

Anonymous Referee #1

- General comments

I appreciate the effort the authors have made to revise the manuscript, including the revision of simulations under a modified set-up. The authors provided useful clarification on many of my initial questions about the simulation set-up; however key questions still remain or are raised by the new set-up that should be clarified before publication. The new dynamics examined by the manuscript are generally not explained clearly enough, particularly the driving forces behind the ice-shelf front circulation cell. Na et al. mention 3-d turbulent structures, but I'd like to see descriptions of the eddies in the IOBL (mentioned on line 177) and those in the PISW. This could help readers understand the simulated dynamics. I appreciate that the authors have offered more information about the oceanographic observations, but the manuscript could still benefit from more discussion of the relationship of LES results to both the oceanographic observations presented and melt rate observations.

- As the reviewer mentioned, there were unclear explanations (e.g. IOBL depth, eddies in IOBL, PISW and comparison with observed melt rate) for our claimed physics. We have amended and added the explanations to clarify the structures and mechanism of these physics.

Added part for the eddies in the PISW and the IOBL:

Figure 2 - In this study, we determined the IOBL region to the depth where the heat flux was 5% of maximum heat flux near the ice shelf base as IOBL physics is analogous to the atmospheric boundary layer (Derbyshire, 1990). Detailed analysis of the IOBL top is discussed at later analysis for the vertical heat flux profile.

Figure 9 – As shown in Figure S4 which depicts the vertical buoyancy flux profiles, PISWs in both weak and strong turbulence cases have a stabilizing effect because of its positively buoyant characteristic. Moreover, PISW in the weak turbulence case has more buoyancy than that in the strong turbulence case because of the momentum difference between the PISWs in the two cases. Subsequently, we determine the PISW top (297 m). Combining the regions where the meltwater and its stabilizing effect dominated with the region where heat entrainment by turbulence was vigorous (5% of maximum heat flux), the IOBL top is determined.

Major revisions:

Methodological questions/concerns that should be addressed in the manuscript text:

● Lines 135-139 do not provide enough detail on how the theoretical velocity profiles are utilized in the model and how this relates to the solution of friction velocity. These are really important details for understanding the momentum fluxes in the ice-ocean boundary layer, the validity of PISW results, and what the steady-state friction velocity means in Figure 2.

- We have amended these phrases to clarify how we used these profiles.

Modified part:

Based on the power-law assumption of turbulent boundary layer flow ($U=U_t\ (z/z_0)^{(1/n)}$), different velocity profiles were composed via different power-law indices, n = 3 (weak turbulence), 4, 5 and 7 (strong turbulence) to resolve the turbulence intensity within IOBL (Irwin, 1979; Kikumoto et al., 2017). These velocity profiles for the four different cases were used at the initialization of the flow field and inlet boundary condition. The freestream (geostrophic) velocity U_t was set as 0.06 m s-1, based on in situ observation near the ice front. The simulation dimensions were 3456 m × 3456 m × 864 m in the x, y, and z directions, respectively. For the simulations, a grid of 288 × 288 × 144 cells was used with a 12m horizontal grid and a 6 m vertical grid with a surface roughness (z_0) of 0.005m (Gwyther et al., 2016).

● I'm troubled by the momentum and heat flux profiles shown in Figure 9. These profiles appear to show that momentum and heat fluxes go to zero at the ice shelf base, implying that there is negligible melting and drag. I found the text addressing these fluxes (paragraph starting on line 279) hard to understand. Can you also relate these fluxes to the spatial evolution of PISW and IOBL as they are advected (i.e., are they gaining or losing heat or momentum)?

- Fluxes at first grid are quite small because the first grid from the ice shelf base was interfacial (right near surface) grid. To examine depths of PISW and IOBL, we have added the dot-line in heat flux profile of Figure 9. PISW (above the 297 m) was always gaining heat and momentum from lower region of IOBL. We have amended this paragraph to clarify the determination of the IOBL top, PISW scale and heat entrainment with Figure S4 (buoyancy flux).

Modified paragraph:

Figure 9 shows the vertical profiles of the vertical fluxes of momentum and heat beneath the ice shelf. As shown in Figure S4 which depicts the vertical buoyancy flux profiles, PISWs in both weak and strong turbulence cases have a stabilizing effect because of its positively buoyant characteristic. Moreover, PISW in the weak turbulence case has more buoyancy than that in the strong turbulence case because of the momentum difference between the PISWs in the two cases. Subsequently, we determine the PISW top (297 m). Combining the regions where the meltwater and its stabilizing effect dominated with the region where heat entrainment by turbulence was vigorous (5% of maximum heat flux), the IOBL top is determined. In the strong turbulence case, the vertical momentum flux is negative and its maximum is located within IOBL (IOBL top - 319 m depth). This implies that the momentum entrainment from the sub-ice shelf plume to IOBL is effective, having large heat entrainment. However, the depth of maximum negative flux in the weak turbulence case is located at 347 m, slightly away from the IOBL. This difference causes the difference in heat flux magnitude at the PISW top. Negative heat flux at 320–400 m depths denotes that some of the entrained heat by the intrusion of the outer ocean is transferred to the downward direction. For steady basal melting, positive heat flux has to remain within the IOBL through flow advection penetrating the stratified IOBL. The maximum positive heat flux for the weak and strong turbulence cases is 138, 213 W m^{-2}, respectively, with a 54% difference. This difference is comparable with a difference (66%) in the melting rate near the ice front, confirming that basal melting is proportional to the amount of heat flux and entrainment by flow advection penetrating the stratified IOBL.

● The calculation of the freezing rate in the open ocean is not included in the methods. Is it permitted only at the surface or throughout the water column? There should be associated caveats in the Methods and Discussion about potential frazil ice effects not considered in your simulations, with citations to existing literature on frazil ice effects.

- Freezing rate was also calculated by same equations of melting rate with different ambient values of temperature and salinity. It is flux boundary at sea surface (permitted only at the surface). We have added the part about potential frazil ice effects in the Discussion section.

Added phrase:

These fluxes for the melting and the freezing rates were applied at the first grid from the ice shelf base or sea surface.

Furthermore, the effect of frazil ice dynamics (e.g. crystal growth rate, nucleation and gravitational removal) in sea surface or marine ice should be investigated because the change in plume characteristics and amount of temperature and salinity is highly related with frazil ice dynamics (Galton-Fenzi et al., 2012; Rees Jones and Wells, 2018).

● You imply on line 329 that you aren't using a dynamic SGS model but on line 110 you have included a dynamic SGS equation.

- In this study, we used the Deardorff SGS model with constant model coefficient (C_m=0.1) and mixing length. We have amended this part to clarify this.

Modified phrase:

where l is the turbulent mixing length (depends on wall distance, grid spacing and stratification), Δ is the length scale of the filter and ρ_θ is potential density.

- The thermodynamics of the ice-shelf front are not addressed. Do you allow lateral melting?

- In this study, we did not consider lateral melting of ice front with assumption that lateral melting is not significant. Thermal driving at lateral melting is low because outer ocean temperature is comparable with freezing temperature at depth from 0 m to 140 m, and existence of PISW at depth from 140 m to 280 m. We have added this to the methodology section.

Added phrase:

In this study, the lateral melting at the ice shelf front is not included based on assumption that the lateral melting is negligible because of extremely low thermal driving at the lateral side of the ice shelf front.

The introduction of an ice-front circulation cell warrants further explanation of these dynamics than is currently included in the manuscript. On line 187, the authors write "the development of this circulation is mainly induced by the downward force of salt flux by sea ice formation and the shear stress of sub-ice shelf plume." How does sea-ice formation relate to downwelling? I'd expect convective mixing. What role does sub-ice shelf plume momentum play? Since winds are excluded, how might the results change if winds were included? Is the hypothesized circulation cell compatible with observed sea ice advection patterns? How is this similar to or different from the role that ice-shelf meltwater plays in this study: Malyarenko, A., Robinson, N. J., Williams, M. J. M. & Langhorne, P. J. 2019. A wedge mechanism for summer surface water inflow into the Ross Ice Shelf cavity. Journal of Geophysical Research: Oceans. 10.1029/2018JC014594

- As the reviewer mentioned, downward force is induced by convective mixing at local salt maximum (x = 1766 m (n=3), 1688 m (n=7)). To clarify this, we added the concept of inner ice front circulation near ice front. Between inner and outer circulations, there is local salt maximum. Those circulations share the downward force of the salt flux. The role of sub-ice shelf plume momentum is momentum transport from plume to upper layer via shear stress, and this shear force is contributing to the formation of outer ice front circulation. Inner circulation is induced by upwelling of PISW plume and salt flux and outer circulation is induced by salt flux and shear force by sub-ice shelf plume. These characteristics can be observed in circulation-stretching direction. We cannot find sea ice advection patterns which is corresponding to our simulation domain scale.

- As the reviewer mentioned, the inclusion of wind stress can affect the scale and magnitude of circulations. The effect of wind stress will be considered in future study because our objective in this study is to examine the detailed physics in the sub-ice shelf environment.

- In terms of meltwater accumulation at the sea surface near the ice front (it is clearly observed in temperature contour of Figure 3), our findings can be a supportive evidence for the mechanism of wedge formation and a thin layer of local meltwater outflow in basal melting input. However, we think that ice shelf front ablation (lateral melting) is not significant in ocean conditions of our study. We have added this to discussion section.

Modified phrase:

Figure 3 - In the ocean region, velocities in cases with weak and strong turbulence had similar patterns for two ocean circulations in the upper ocean region (0–280 m depth). In this study, we refer to these circulations as the “ice front circulations”. Since we did not impose the wind effect at the top boundary, we can conclude that the development of outer circulation is mainly induced by the downward force (convective mixing) of the salt flux by sea ice formation as well as the shear stress by the momentum difference between the upper region and sub-ice shelf plume. Moreover, the development of the inner circulation is mainly due to the upwelling of the buoyant water and the downward force of the salt flux. Thus, the inner circulation is stretched in the vertical direction, whereas the outer circulation is stretched in the horizontal direction. The downward force that the two circulations share pushes the sub-ice shelf plume, moving the stratification line (280 m depth) near the ice shelf to about 350 m depth.

Discussion - Moreover, PISW upwelling and its accumulation near the sea surface could evidentially support the wedge formation mechanism proposed by Malyarenko et al. (2018).

The relationship between LES results and oceanographic observations also warrants further explanation. You say (line 216) that the signature of PISW is in the CTD profiles but it is unclear what this signature is in relation to Figure 4.

- We have added the explanation for the relationship between LES results and oceanographic observation.

Added phrases:

One of them is why the sub-ice shelf plume is located below 400 m depth even though the ice shelf base is located at 280 m depth. The LES results show that the downward force of the salt flux and the development of the inner ice front circulation (Figure 3) push the stratification line near the ice shelf. Second is the existence of relatively low-temperature water (–1.96 °C) at 100 m depth. This feature can be explained by the PISW upwelling process. Through the comparison of quantity and its characteristics, we conclude that the LES results are similar to the in situ observations of oceanic environments, in terms of the physical process of ocean circulation and the magnitude of the main variables.

The agreement between the simulated ice-shelf melt rate distribution and the observed melt rate distribution also needs to be discussed.

- We have added the part for comparison between observed melt rate (Wray, 2019) and melt rate obtained by our LES result.

Added phrases:

The melt rate for the strong turbulence case is quite low (1.74 fold) compared to the observed melt rate (0.42 m yr^{-1}) proposed by the study of Wray (2019), which is about basal channel near the NIS front. However, the melt rate in our LES results is comparable to the observed melt rate, considering the change of heat transfer coefficient by thermal driving and the difference of thermal driving (0.032°C in our LES simulations and 0.14°C in the study of Wray (2019)). The heterogeneous patterns of melting rate in the meridional direction (parallel direction to the ice front) are not noticeable.

The explanation for heterogeneous PISW upwelling is unclear to me. I think it would help to see a planar view of ice-shelf cavity circulation. I wonder if the boundary conditions imposed may be influencing the circulation to a greater extent in the high turbulent shear case.

- As the reviewer recommended, we have examined the horizontal contour to find the cause of PISW upwelling and heterogeneous freezing pattern. As shown in new Figure S2, there are PISW layer induced by PISW upwelling and large scale disturbance of outer ocean. In weak turbulence case, strong PISW layer with strengthen inner ice front circulation block the intrusion of outer ocean intrusion. However, weak PISW layer in strong turbulence case cannot block the intrusion of outer ocean with baroclinic eddy, causing a heterogeneous pattern of PISW and freezing pattern. We have amended the part for heterogeneous pattern with new Figure S2.

Modified phrase:

This feature is highly related to its perturbation scale of the outer ocean (Rossby radius of deformation) and PISW upwelling (Figure S2). In the weak turbulence case, PISW upwelling occurs along the ice front edge, comprising a strong, narrow PISW layer near the ice front with strengthened inner ice front circulation and this blocks an intrusion of the outer ocean with baroclinic eddy. However, it is observed the heterogeneous patterns of PISW and freezing rate in strong turbulence case, because the PISW layer near the ice front is wide and weak, permitting the intrusion of the outer ocean with large baroclinic eddy.

189: “The circulation pushes the sub-ice shelf plume with downward forcing, making that stratification line near ice shelf is moved to about 350 m depth.” Clarify the relative importance of downwelling and mixing for deepening the halocline.

- We have amended this phrase to clarify the downward force is dominant at this depth.

Modified phrase:

The downward force that the two circulations share pushes the sub-ice shelf plume, moving the stratification line (280 m depth) near the ice shelf to about 350 m depth.

204: This paragraph would be a good place to include a comparison of PISW depth and meltwater fluxes between the 4 cases.

- Instead of this paragraph (because PISW cannot be observed clearly in Figure 4), we have added the part for PISW depth and meltwater fluxes with quantification of buoyancy flux (Figure S4) to Figure 9.

Modified phrase:

As shown in Figure S4 which depicts the vertical buoyancy flux profiles, PISWs in both weak and strong turbulence cases have a stabilizing effect because of its positively buoyant characteristic. Moreover, PISW in the weak turbulence case has more buoyancy than that in the strong turbulence case because of the momentum difference between the PISWs in the two cases. Subsequently, we determine the PISW top (297 m). Combining the regions where the meltwater and its stabilizing effect dominated with the region where heat entrainment by turbulence was vigorous (5% of maximum heat flux), the IOBL top is determined.

226: “Because the amount of the PISW in the strong turbulence case is larger than that in the weak turbulence case, its turbulence energy spectra within IOBL (297 m) is the lowest.” This needs more explanation.

- With the definition of PISW depth and IOBL top, we re-plot the turbulence energy spectra within IOBL (291 m) at different zonal distance to show the spatial transition of IOBL flow following the inertial subrange slope ($k \sim -5/3$).

Modified paragraph:

The one-dimensional turbulence energy spectra at 291 m depth (within IOBL) in the cases with weak and strong turbulence are plotted in Figure 5. Moreover, we examine different zonal locations (x = 400, 800, 1200, 1800, 2300 and 2800 m) to observe a spatial transition of the IOBL flow. For a wavenumber greater than 0.002033 m^{-1} which represents the approximately 500 m scale of the energy-containing eddy, the energy spectra of the LES results follow the –5/3 slope of the Kolmogorov scale in the inertial subrange. For the cases with weak and strong turbulence, a similar trend of spatial transition of energy spectra at the IOBL region is observed. At zonal distance of 400 and 800 m, turbulence is under a fully-developed state with a similar magnitude of energy spectra. Near the ice front (1200 m) and right after passing the ice front (1800 m), the turbulence energy spectra are suppressed by the inner ice front circulation and downward forcing. At the region of the outer ice front circulation, the turbulence energy spectra exhibits the highest energy level.

243: “it is shown that the LES model adequately resolves the oceanic flow beneath the ice shelf with the proper thermohaline dynamics by the melting effect beneath the ice shelf and the freezing effect at the sea surface” This is a very general statement. What thermohaline dynamics do you have confidence in?

- As the reviewer mentioned, this phrase was unclear for thermohaline dynamics we emphasized. We have amended this phrase to clarify what thermohaline dynamics we emphasize.

Modified phrase:

The afore-mentioned analysis shows that the LES model adequately resolves the oceanic flow beneath the ice shelf with the thermohaline dynamics, such as IOBL dynamics, PISW upwelling and convective mixing by salt flux at the sea surface.

246: “there are shear forces caused by the momentum of the sub-ice shelf plume and the buoyancy force...” This is not adequately explained. What is the relationship between the stratification, momentum fluxes, and buoyancy? It’s worth reminding the reader that the ice shelf based is not sloped so buoyancy does not drive mean flow.

- As the reviewer mentioned, we have amended this phrase to clarify the flat base of the ice shelf.

Modified phrase:

Since we assumed a flat base of the ice shelf in this study, the buoyant force of PISW does not accelerate the PISW at the ice shelf base. Driving forces within the IOBL flow are shear forces caused by the momentum of the sub-ice shelf plume and the stratification force (stabilizing force) caused by the PISW.

Figure 6: The x-axis appears to span the whole domain, but there should only be freezing at the sea surface in the open ocean part of the domain.

- The x-axis in Figure 6 is from 1280 m (ice front) to 3456 m. We have added the location of the ice front to Figure 6.

Figure 7: Specify whether this figure includes or excludes the region of underdeveloped turbulence.

- This figure includes the region of underdeveloped turbulence. We have added the region of underdeveloped turbulence to Figure 7.

The features we’re seeing in Figure S3 should be explained in the text. I wasn’t able to figure out the difference between right and left panels in this figure.

- To explain the heterogeneous pattern of PISW, freezing rate, we have removed previous Figure S3 and have added the new Figure S2 about the different scales of baloclinic eddy and Rossby radius of deformation. Moreover, we have added the explanation part for this.

Modified Figure S2 and explanation part:

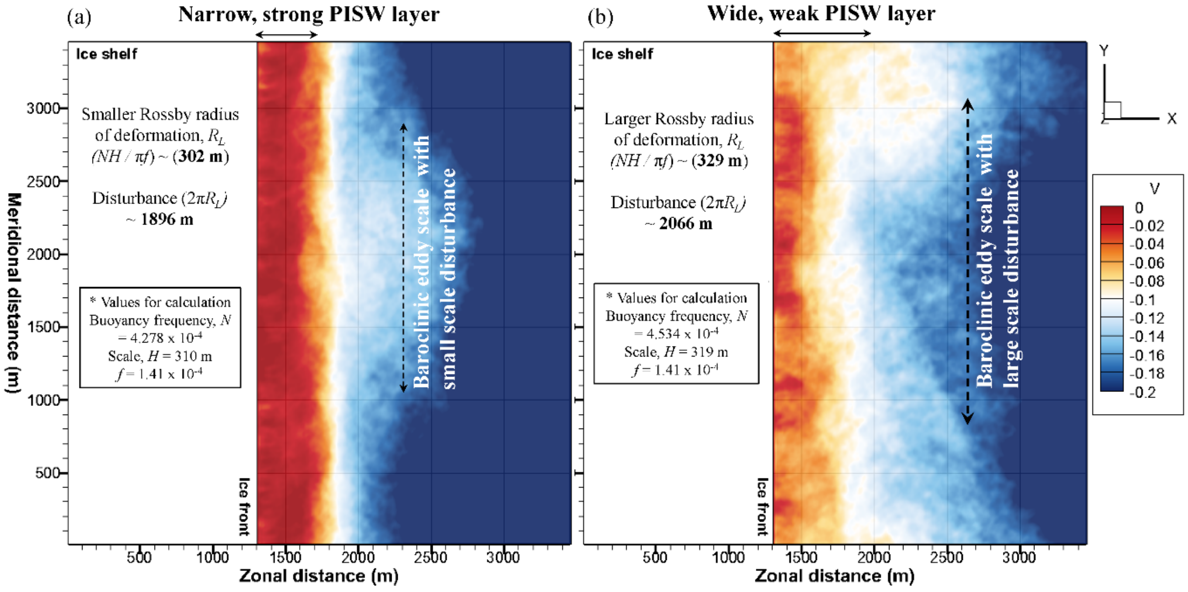

Figure S2. xy distribution of meridional velocity at 3 m depth to estimate baloclinic eddy and Rossby radius of deformation by Coriolis force. Calculation for Rossby radius of deformation is based on depth-averaged buoyancy frequency and depth (scale) between the sea surface and IOBL top.

This feature is highly related to its perturbation scale of the outer ocean (Rossby radius of deformation) and PISW upwelling (Figure S2). In the weak turbulence case, PISW upwelling occurs along the ice front edge, comprising a strong, narrow PISW layer near the ice front with strengthened inner ice front circulation and this blocks an intrusion of the outer ocean with baroclinic eddy. However, it is observed the heterogeneous patterns of PISW and freezing rate in strong turbulence case, because the PISW layer near the ice front is wide and weak, permitting the intrusion of the outer ocean with large baroclinic eddy.

317: It sounds as if you're saying that PISW is transferring momentum to IOBL in the ice-shelf cavity. Where is this momentum coming from?

- That phrase was wrong. We have amended this phrase.

Modified phrase:

High turbulence intensity causes strong momentum transfer, resulting in increased melting and high-speed currents within the IOBL.

322: Explain how the circulation is similar to centrifugal overturning.

- In our study, we observed the PISW upwelling (gravitational instability) with its baroclinic eddy (centrifugal instability), showing that baroclinic eddy and its vorticity is corresponding to PISW momentum and Ekman layer. These mechanisms are similar with mechanism proposed by Naviera

Garabato (2017). We have amended this phrase, clarifying the specific mechanisms proposed by Naviera Garabato (2017).

Modified phrase:

Similar to the observation of Naveira Garabato et al. (2017), we also observe the PISW upwelling (gravitational instability) and the development of its baroclinic eddies (centrifugal instability by density gradient) with a strong Ekman layer.

330: How will the findings be used to interpret observations?

- In revised manuscript, we have added the part for the relationship between some features of the observations and how we explain these features. We have amended this phrase to clarify how our findings can be used to interpret features of observations.

Modified phrase:

One of them is why the sub-ice shelf plume is located below 400 m depth even though the ice shelf base is located at 280 m depth. The LES results show that the downward force of the salt flux and the development of the inner ice front circulation (Figure 3) push the stratification line near the ice shelf. Second is the existence of relatively low-temperature water (–1.96 °C) at 100 m depth. This feature can be explained by the PISW upwelling process. Through the comparison of quantity and its characteristics, we conclude that the LES results are similar to the in situ observations of oceanic environments, in terms of the physical process of ocean circulation and the magnitude of the main variables.

The main findings and claimed mechanism of this study can be used to fill the gap in the sub-ice shelf cavity observation.

Minor revisions:

23: “which in turn slows sea level rise” This can be misleading because the rate of sea level rise may increase when ice shelves are removed but not necessarily when the ice sheet reaches a new equilibrium without the ice shelf.

- We have amended this phrase to avoid the misleading.

Modified phrase:

One of the important roles of ice shelves in controlling the mass balance of the AIS is to hinder the flow of inland ice into the ocean to prevent sea level rise (Holland et al., 2020).

The authors provided more detail about the CTD and ADCP data collection, which was appreciated.

One remaining detail that would be useful to the reader is the distance between the ice front and the observations.

- We have added information for the distance between ice front and the observation.

Added part:

The observation location is approximately 1 km away from the ice front.

Specify t* in hours.

- t^* in four cases is listed up in Table 2. We have the reference of Table 2 in this paragraph.

Added part:

Table 2 presents these friction velocities and the large-eddy turnover times for the four cases.

Thank you for clarifying the velocity orientation in this revision. I think it's also worth pointing out to the readers that the zonal velocity is perpendicular to the ice-shelf front geometry (especially in the caption for Figure 3), even though this can be seen in the new figure.

- As the reviewer mentioned, we have added the part for pointing out that the zonal velocity is perpendicular direction to the ice front. Moreover, we have added this in the caption for Figure 3.

Added phrase:

After passing the ice shelf, this high-speed current flows in the perpendicular direction to the ice front.

(Caption for Figure 3) In these contours, the zonal direction is perpendicular to the ice shelf front.

128: I think the notation should be S(z_1) rather than Sa(z_1) since you use S_b.

- As the reviewer mentioned, we have amended the notation.

261: The way this is written, there is an apparent inconsistency in the strong turbulence case that it has the smallest mean shear gradient, highest TKE, yet you say that TKE production is proportional to mean shear gradient and turbulent shear stress.

- Turbulence kinetic energy production $(-u'w'\frac{\partial u}{\partial z})$ is highest in strong turbulence case. Therefore, we can know that turbulent shear stress $(-u'w')$ is highest, showing that turbulent shear stress has a larger portion of turbulent kinetic energy production than mean shear gradient, because mean shear gradient ($\frac{\partial u}{\partial z}$) is smallest in strong turbulence case. We have amended this phrase to clarify this.

Modified phrases:

The strong turbulence case displays the smallest mean shear gradient but the largest turbulence intensity, whereas the weak turbulence case has an opposing features. Since the turbulence kinetic energy production is proportional to the mean shear gradient and turbulent shear stress (Pope, 2000), turbulent shear stress is the highest in the strong turbulence case, showing that the turbulent shear stress has a large portion of turbulent kinetic energy production.

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300 “we used the LES model with proper boundary conditions” “proper” isn’t appropriate here, as it is quite subjective.

- We have amended this word to *in-situ* based boundary conditions

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Section 4.2. It would be helpful to mention the temperature difference between PISW as it exits the cavity and the sea surface freezing point.

- We have added the temperature difference between interfacial temperature (not freezing temperature) and PISW at the ice shelf base because melt rate is also calculated based on interfacial temperature.

However, the melt rate in our LES results is comparable to the observed melt rate, considering the change of heat transfer coefficient by thermal driving and the difference of thermal driving (0.032°C in our LES simulations and 0.14°C in the study of Wray (2019)).

319: “showing that this result is in agreement with the previous study of Jenkins (2016)” This is too general. It’s simply that both this study and Jenkins have Ekman layers below the ice shelf, right?

- We have amended this phrase, referring the specific case and physics in Jenkins (2016).

Modified phrase:

Furthermore, a turbulent Ekman layer developed in all cases, showing that these classical Ekman layers are similar to the non-inclined ice shelf case of Jenkins (2016) in terms of the steady Ekman layer independent of thermal driving broadening.

327: “constant turbulent coefficients in SGS model” Which coefficients? I thought you were using a dynamic SGS model.

- We have amended this phrase to avoid misleading.

335: It’s unclear what effects you’ll be examining with the “vertical distribution of pressure”

- We have removed these words.

336: “With better understanding of various parameters on basal melting” Which parameters?

- Parameters mean afore-mentioned important factors. We have amended this phrase.

Modified phrase:

A better understanding of the effect of important factors on basal melting and its meltwater dynamics will help in the improvement of the parameterizations (e.g. vertical mixing within the IOBL and sea-ice formation and behavior) in the regional ocean model.

The schematic diagram (Figure 10) is a great addition to the manuscript. I do find it somewhat confusing to include katabatic winds in the schematic when they do not play a role in your explanation of the dynamics, particularly as they appear to be opposed to the ice front circulation pattern.

- As the reviewer mentioned, katabatic winds can be somewhat confusing. We have removed this.

There are several places where the meaning of the text is unclear:

16: “In the strong turbulence case, there are distinct features in basal melting and flow characteristics.” This is too vague.

- As the reviewer mentioned, this phrase is too vague. We have amended this phrase to clarity what we observe.

Modified phrase:

In the strong turbulence case, distinct features are present in the high momentum of meltwater with a strong Ekman layer and the large scale of the baroclinic eddies.

30 “The driving forces for basal melting in cold water cavity are shear force by tidal mixing and the thermohaline process by sea ice formation” Both of these forcings need more introduction and explanation here.

- We have added more explanation with reference in this phrase.

Modified phrase:

Shear force generated by tidal mixing and the thermohaline process during sea ice formation are the basal melting driving forces in cold water cavity (e.g., high salinity shelf water), whereas the intrusion of circumpolar deep water (CDW), which is the water well above the local freezing temperature, is the main driving force for basal melting in the warm-water cavity (Davis and Nicholls, 2019; Jacobs et al., 1992; Yoon et al., 2020).

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35 “Therefore, because driving forces from the ocean and opposite forces by the meltwater merge within the boundary layer” I don’t know what is meant here. What forces?

- We have amended this phrase to clarify the forces for IOBL.

Modified phrase:

The ice shelf–ocean boundary layer (IOBL), which is the boundary layer (meters to tens of meters) right beneath the ice shelf, is difficult to investigate because the shear forces from the ocean and stabilizing force of the meltwater combine within the IOBL (Begeman et al., 2018; Naveira Garabato et al., 2017).

43: “Similar features for weak stratification” Which features are you referring to?

- We refer to moderate melt rate with low thermal driving.

Modified phrase:

Similar melt rates for weak stratification were also observed beneath the Fimbul and Ross ice shelves (Arzeno et al. 2014; Hattermann et al., 2012).

48: “controlling the shear impact of its momentum” Please clarify

- As the reviewer mentioned, this phrase was vague. We change this to “Occurring the shear by buoyant moving of meltwater”.

Modified phrase:

Positively buoyant sub-ice shelf plumes created near the grounding line can affect the stratification and heat entrainments within the IOBL; they yield the shear because of the buoyant moving of meltwater near the grounding line and ice shelf front (Hewitt, 2020; Holland and Jenkins, 1999).

57: “In order to find out the effects of various forcing clearly” Please specify which forcings

- We have amended this phrase to specify which forcing.

Modified phrase:

To clearly determine the effects of various forcing (e.g. shear, stabilizing force of the meltwater and buoyant moving of meltwater), independent experiments or observations for the forcing are needed.

185: “velocities in two cases” Which two cases?

- “Cases with weak and strong turbulence” We have amended this phrase.

211: “upper streamwise direction” Would be more clear to put in terms of zonal/meridional or parallel/perpendicular to ice front

- We have amended this word to perpendicular direction to ice shelf front.

302: “Additionally, we set to ambient values” set what to ambient values?

- We have amended this without “to”.

356: “it means that stratified forcing by PISW has a nonlinear feature for flow shear by strong turbulence”

- We have amended this phrase without “nonlinear”.

Modified phrase:

However, the stratification intensity in the four different turbulence cases did not exhibit a distinct trend, denoting that the stratified forcing by PISW varies according to the flow shear caused by turbulence.

332: “this study can be improved by comparing LES results with observations and their feedback” “and their feedback” is unclear.

- We have added the example in this phrase

Modified phrase:

If direct observation for the IOBL flow structures and turbulence characteristics in the sub-ice shelf environment is available, this study can be improved by comparing LES results with observations and their feedback (e.g. correction of ambient values and transfer coefficients).

There are also several places where the grammar needs revision:

9. “but there is a poor understanding of the fluid dynamic, thermohaline physics of the IOBL flow”

- We have amended this phrase.

Modified phrase:

Ice melting beneath Antarctic ice shelf is caused by heat transfer through the ice shelf–ocean boundary layer (IOBL); however, our understanding of the fluid dynamic and thermohaline physics of the IOBL flow is poor.

11: “velocity’s theoretical profile” >> “theoretical profile for velocity”

- As the reviewer mentioned, we have amended this phrase.

28: “The sub-ice shelf oceanic environment can be divided into broad classifications” >> “The sub-ice shelf oceanic environment can be divided into two classes”

- As the reviewer mentioned, we have amended this phrase.

38: “physics in ice shelves” >> “physics below ice shelves”

- As the reviewer mentioned, we have amended this phrase.

69: “Nansen Ice Shelf (NIS; cold-water cavity)” >> “Nansen Ice Shelf (NIS), a cold-water cavity,”

- As the reviewer mentioned, we have amended this phrase.

72: “while remaining thermohaline forcing by the melting and freezing”

- We changed this phrase to clarify our forcing.

Modified phrase:

For consistency in experiments, we considered different turbulence state while keeping the same thermohaline forcing by the melting and freezing.

177: “are highly fluctuated in” >> “greatly fluctuated during”

- As the reviewer mentioned, we have amended this part.

178: “As turbulence within IOBL is stronger, the magnitude of fluctuation is larger.”

- We have amended this phrase, referring large-scale eddy.

Modified phrase:

As the turbulence near the IOBL is stronger, the large-scale eddy corresponding to the Rossby radius of deformation is larger (Figure S2).

189: “Noticeable difference between the two cases” >> “A noticeable difference between the two cases”

- As the reviewer mentioned, we have amended this phrase.

194: “with different momentum along to streamwise direction in two cases.”

- We have amended this phrase.

Modified phrase:

These momentum differences in the two cases mainly affects the magnitude and scale of the ice front circulations.

307: “for resolving the IOBL and oceanic flow in reality” >> “for simulating the IOBL and oceanic flow more realistically”

- As the reviewer mentioned, we have amended this part.

Anonymous Referee #2

General comments:

This study uses large-eddy simulations (LES) to examine the effect of turbulence in the ice- shelf-ocean boundary layer (IOBL) of Nansen Ice Shelf. The simulations are based on recent observations of ocean conditions near the Nansen Ice Shelf. The dynamics are forced by a neutrally buoyant plume moving beneath the ice shelf and penetrating into the open ocean. Key results are the basal melt rate of the ice shelf and the freezing occurring at the ocean surface (modelling sea ice formation), both of which increase when the plume is more turbulent. The authors also attempt to discuss some interesting heterogenous structures in terms of Ekman layer dynamics, but I did not follow this explanation as it stands.

The study is of some interest and has been improved from the previous iteration. The new simulations have an idealised velocity input condition to model a plume with four different levels of turbulence. The temperature and salinity input conditions are broadly based on observations taken further away from the ice shelf. The scientific premise (what happens when turbulence is increased?) is much clearer. There are few LES of sub-ice shelf flow, in particular with the aim to match observations. I think that the study has potential for publication, but I have some comments that I would like to see addressed first.

Specific comments:

1. The authors vary only the shape of the input velocity profiles across the four runs. As the set-up is so constrained (in terms of setting specific input profiles of velocity, temperature and salinity) I wonder what portion of the results are caused by the input conditions versus the dynamics in the system. What do the authors expect would happen if there was no basal melt? Would there still be plenty of mixing in the sub-ice shelf flow, and would we still see the increase in surface freezing at the ice edge? Similarly, if the surface freezing was turned off, how would this change the outflowing plume dynamics?

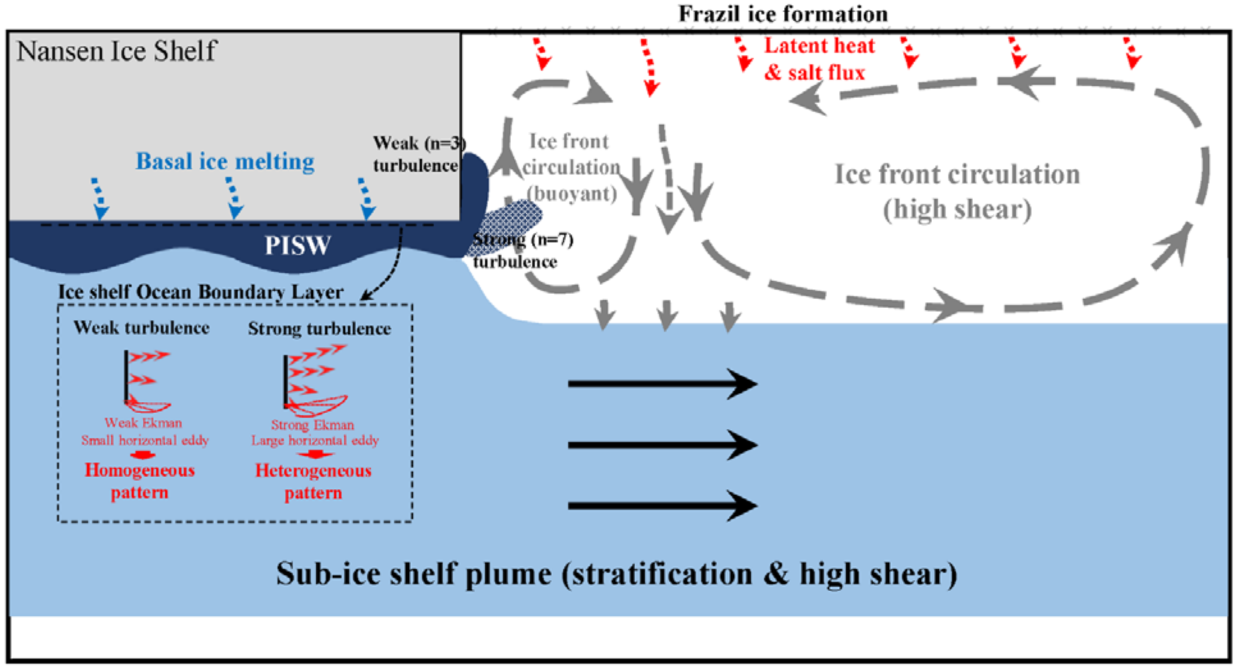
- As input conditions are varied, shear force and turbulent intensity within IOBL can be changed, having change in a vertical momentum flux and vertical heat transport. If there is no basal melt, similar trend is also observed, in terms of momentum and heat flux beneath the ice shelf. However, if there is no PISW, PISW upwelling is not occurred and of the shape and the magnitude of ice front circulations are changed. Similarly, if there is no surface freezing, ice front circulation can be shrink or disappear because the absent of downward forcing and convective mixing.

We have amended the figures and explanations to clarify these dynamics by thermohaline process of melting or freezing.

Modified paragraph for Figure 3:

In the ocean region, velocities in cases with weak and strong turbulence had similar patterns for two ocean circulations in the upper ocean region (0–280 m depth). In this study, we refer to these circulations as the “ice front circulations”. Since we did not impose the wind effect at the top boundary, we can conclude that the development of outer circulation is mainly induced by the downward force (convective mixing) of the salt flux by sea ice formation as well as the shear stress by the momentum difference between the upper region and sub-ice shelf plume. Moreover, the development of the inner circulation is mainly due to the upwelling of the buoyant water and the downward force of the salt flux. Thus, the inner circulation is stretched in the vertical direction, whereas the outer circulation is stretched in the horizontal direction. The downward force that the two circulations share pushes the sub-ice shelf plume, moving the stratification line (280 m depth) near the ice shelf to about 350 m depth. A noticeable difference between the two cases is observed near the ice front and beneath the ice shelf. At depths from 280 to 320 m (IOBL region), high zonal velocity beneath the ice shelf is observed in the strong turbulence case (n = 7). After passing the ice shelf, this high-speed current flows in the perpendicular direction to the ice front.

Modified Figure 10:



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2. I disagree with (or perhaps I did not understand) the Ekman layer explanation for the heterogeneity seen in the strong turbulence cases. I agree that stronger velocities beneath the ice shelf could lead to a stronger Ekman layer, but why wouldn't this be a homogenous response underneath the whole ice shelf? What is constraining the length scale of the heterogeneity? (E.g. could it alternatively be a baroclinic eddy with a Rossby radius of deformation?) I would appreciate more discussion on these points and an in-depth explanation of the physical mechanisms.

- As the reviewer mentioned, there was no explanation for length scale of the heterogeneous pattern of PISW and freezing. As the reviewer recommended, we examined meridional velocity (parallel to ice front) at sea surface and the baroclinic eddy with a Rossby radius of deformation based on buoyancy frequency, depth (310 m) between sea surface and IOBL and Coriolis parameter. As new Figure S2, wave-like features of baloclinic eddy are observed in meridional velocity and its scale is larger in strong turbulence case. Moreover, the layer of upwelling PISW near the ice front is wide and weak (more advective) in strong turbulence case. Therefore, we conclude that strong and narrow PISW layer blocks the intrusion of outer ocean by the baroclinic eddy in weak turbulence case, whereas weak, wide PISW layer cannot block the intrusion of outer ocean, having a heterogeneous pattern which is corresponding to Rossby radius of deformation.

We have added new Figure S2 and related explanations.

Modified Figure S2:

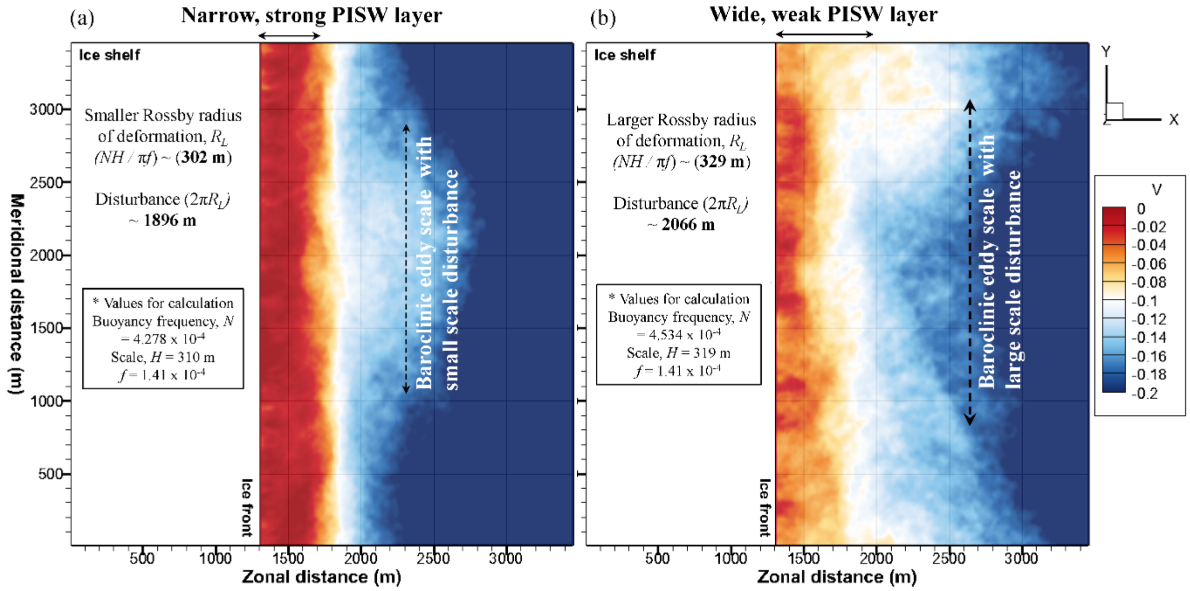

Figure S2. xy distribution of meridional velocity at 3 m depth to estimate baloclinic eddy and Rossby radius of deformation by Coriolis force. Calculation for Rossby radius of deformation is based on depth-averaged buoyancy frequency and depth (scale) between the sea surface and IOBL top.

This feature is highly related to its perturbation scale of the outer ocean (Rossby radius of deformation) and PISW upwelling (Figure S2). In the weak turbulence case, PISW upwelling occurs along the ice front edge, comprising a strong, narrow PISW layer near the ice front with strengthened inner ice front circulation and this blocks an intrusion of the outer ocean with baroclinic eddy. However, it is observed the heterogeneous patterns of PISW and freezing rate in strong turbulence case, because the PISW layer near the ice front is wide and weak, permitting the intrusion of the outer ocean with large baroclinic eddy.

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3. I think more can be done to compare against other cases, in particular Naveira Garabato et al. (2017). (Side note: this study seemed to be missing from the citation list in the manuscript.) The only comparison with the Naveira Garabato et al. study was L321 “These physics with the Ekman layer and the upwelling behavior of PISW are similar to centrifugal overturning instability and lateral shear proposed by Naveira Garabato et al. (2017).” I was confused by this. Are the authors saying that the mechanisms are similar? And if so, how similar and what are the differences? Again, I would appreciate a more in-depth explanation of the exciting phenomena that is noted in this study. I think this would really strengthen our understanding of the phenomena we might expect to see sub-ice shelf and on the ice edge.

- As the reviewer mentioned, previous comparison for the Naveira Garabato et al. study was too vague. We have amended this part to clarify that our mechanism is similar with that of Naveira Garabato et al. study.

Modified phrase:

Similar to the observation of Naveira Garabato et al. (2017), we also observe the PISW upwelling (gravitational instability) and the development of its baroclinic eddies (centrifugal instability by density gradient) with a strong Ekman layer.

L11: In the abstract "…we impose velocity's theoretical profile varying the power-law index." Consider rephrasing as I did not know what "velocity's theoretical profile" meant when I first read through. Highlight that the velocity profile is varied and therefore turbulence is also changed.

- As the reviewer mentioned, we have amended this phrase.

Modified phrase:

To resolve the different turbulence states, we impose the theoretical profile of velocity at the turbulent boundary layer by varying the power-law index.

L35: "Therefore, because driving forces from the ocean and opposite forces by the meltwater merge within the boundary layer (meters to tens of meters) right beneath ice shelf, which is known as the ice shelf–ocean boundary layer (IOBL), we have to investigate the IOBL flow and its structure to reveal the basal melting physics in ice shelves (Holland et al., 2020)." This was a long sentence and a bit unclear. Please consider rephrasing.

- As the reviewer mentioned, we have divided and amended this phrase.

Modified phrases:

The ice shelf–ocean boundary layer (IOBL), which is the boundary layer (meters to tens of meters) right beneath the ice shelf, is difficult to investigate because the shear forces from the ocean and stabilizing force of the meltwater combine within the IOBL (Begeman et al., 2018; Naveira Garabato et al., 2017). Therefore, the IOBL flow and its structure need to be investigated with a turbulence resolving model to reveal the basal melting physics below ice shelves (Jenkins, 2016; Holland et al., 2020).

L135: The power-law equation U=U_t (z/z_t)^(1/n). Firstly, I assume the x signified multiply and not x-direction (was written in the manuscript as U=U_t x (z/z_t)^(1/n))? Secondly, is z_t the surface roughness? Thirdly, when I quickly plotted this power law I got something that looked different to the Figure 2 inset. So how does this equation directly relate to the profiles in Figure 2 inset? Is there some normalisation coming in to play? Finally, are there other studies (apart from Irwin 1979) that have used these profiles? I am wondering if the justification for the plume shape can be strengthened by citing some more studies that use these profiles.

- Firstly, x means multiply as the reviewer mentioned. Secondly, z_t (z_0 in revised manuscript) is surface roughness. Thirdly, we had a confusion for plotting power law profiles. We have changed the inset profile in Figure 2. Finally, we have added the reference which is about power law fitting study for stable boundary layer.

Modified phrases:

Based on the power-law assumption of turbulent boundary layer flow ($U=U_t\ (z/z_0)^{(1/n)}$), different velocity profiles were composed via different power-law indices, n = 3 (weak turbulence), 4, 5 and 7 (strong turbulence) to resolve the turbulence intensity within IOBL (Irwin, 1979; Kikumoto et al., 2017). These velocity profiles for the four different cases were used at the initialization of the flow field and inlet boundary condition. The freestream (geostrophic) velocity U_t was set as 0.06 m s-1, based on in situ observation near the ice front. The simulation dimensions were 3456 m × 3456 m × 864 m in the x, y, and z directions, respectively. For the simulations, a grid of 288 × 288 × 144 cells was used with a 12m horizontal grid and a 6 m vertical grid with a surface roughness (z_0) of 0.005m (Gwyther et al., 2016).

L152: The wind effect is excluded in the simulations by setting the surface velocity to zero, even though observations showed a non-zero value of wind. In the reply to reviewers there was some justification for the zero velocity condition, would it be possible to have the brief explanation included in the manuscript also?

- As the reviewer mentioned, we have added the brief explanation for zero velocity at the sea surface.

Modified phrase:

The cyclic boundary condition was applied to lateral boundaries, while a Dirichlet boundary condition (Utop = 0 m s-1) was imposed on the top layer. Zero velocity at the sea surface implies the exclusion of the wind effect to examine the ocean dynamics caused by the sub-ice shelf plume solely.

Section 2: I might have missed this, but what was the surface freezing condition on temperature and salinity? Was it a Dirichlet or flux condition?

- Melting and freezing conditions in this study are flux condition based on Monin-Obukhov similarity.

L175: How was the large-eddy turnover time calculated here?

- Large-eddy turnover time is calculated by IOBL characteristic length (IOBL top) divided by friction velocity. We have added the brief explanation to this part.

Modified phrase:

The total simulation time (96 h) is normalized by large-eddy turnover time (t*) which is calculated by the scale of overturning large eddy within the IOBL divided by the friction velocity.

Figure 2: There is a lot of variability in this figure, which makes it difficult to determine whether it is in equilibrated state. Are there other results that show the simulations are equilibrated?

- As the reviewer mentioned, a lot of variability could be induced by large-scale disturbance (baroclinic eddy). We have added the phrase for explanation of this.

Modified phrase:

As the turbulence near the IOBL is stronger, the large-scale eddy corresponding to the Rossby radius of deformation is larger (Figure S2).

Results: Are there any indications of inertial waves present in the simulations, due to having Coriolis parameter (f)? I am wondering if this variability would appear on the friction velocity (Figure 2).

- Because the disturbance by baroclinic eddy (larger scale in strong turbulence) affects to IOBL dynamics, this variability of the disturbance appears on the friction velocity. We have added this in Figure 2 explanation.

Modified phrase:

As the turbulence near the IOBL is stronger, the large-scale eddy corresponding to the Rossby radius of deformation is larger (Figure S2).

Figure 5: Caption does not seem to be consistent with legend. What is the difference between (a) and (b) figures? If it is n=3 and n=7, then why are these values also varied in the legend?

- With new definition of PISW depth and IOBL depth, we replot the energy spectra at different zonal distance to observe development and change of turbulence within the PISW.

Modified paragraph for Figure 5:

The one-dimensional turbulence energy spectra at 291 m depth (within IOBL) in the cases with weak and strong turbulence are plotted in Figure 5. Moreover, we examine different zonal locations (x = 400, 800, 1200, 1800, 2300 and 2800 m) to observe a spatial transition of the IOBL flow. For a wavenumber greater than 0.002033 m^{-1} which represents the approximately 500 m scale of the energy-containing eddy, the energy spectra of the LES results follow the –5/3 slope of the Kolmogorov scale in the inertial subrange. For the cases with weak and strong turbulence, a similar trend of spatial transition of energy spectra at the IOBL region is observed. At zonal distance of 400 and 800 m, turbulence is under a fully-developed state with a similar magnitude of energy spectra. Near the ice front (1200 m) and right after passing the ice front (1800 m), the turbulence energy spectra are suppressed by the inner ice front circulation and downward forcing. At the region of the outer ice front circulation, the turbulence energy spectra exhibits the highest energy level.

L239: Could the spatial-averaged freezing rate values also be included here? Perhaps an earlier reference to Table 2 would help (first time you reference Table 2 is in Section 4.2 Discussion)?

- As the reviewer mentioned, we have added the earlier reference to Table 2 (Figure 2 part)

Modified phrase:

Table 2 presents these friction velocities and the large-eddy turnover times for the four cases.

L262: “Because turbulence kinetic energy production is proportional to mean shear gradient and turbulent shear stress, turbulent shear forcing is highest in the strong turbulence case.” Could a citation please be included for the first half of this sentence?

- We have added the reference of Pope (2000) for this.

Figure 9: There are some negative heat flux values below the positive values in the IOBL. What is causing this?

- At depth from 320 m to 400 m, negative heat flux (downward heat transport) is observed. It is from the heat entrainment by interaction of outer ocean. Entrained heat at depth from 320 m to 400 m is transferred to upward and downward direction, by in-there turbulence. We have added this explanation to Figure 9 part.

Modified phrase:

Negative heat flux at 320–400 m depths denotes that some of the entrained heat by the intrusion of the outer ocean is transferred to the downward direction

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Section 4.2: There are a few different ideas discussed in this section. Please consider breaking into separate paragraphs.

- As the reviewer mentioned, Section 4.2 in revised manuscript is divided to two paragraphs.

L324: Please include a definition for the flux Richardson value. How was it calculated in the simulations?

- As the reviewer mentioned, we have added the definition for the flux Richardson number. We calculated this value using $3t^*$ averaged 3d-flow field data.

Technical corrections:

L34: “opposite forces” perhaps “opposing forces”?

- To clarify the force we consider, we have amended this phrase.

Modified phrase:

The ice shelf–ocean boundary layer (IOBL), which is the boundary layer (meters to tens of meters) right beneath the ice shelf, is difficult to investigate because the shear forces from the ocean and stabilizing force of the meltwater combine within the IOBL (Begeman et al., 2018; Naveira Garabato et al., 2017).

L70: Here and in several other places there is a “the” missing (e.g. “THE main parameter…”).

- In revised manuscript, we have edited this manuscript with copyediting services of skilled editor.

L71: “For consistency in experiments, we considered different turbulence state while remaining thermohaline forcing by the melting and freezing.” Was this meant to be more along the lines of: “For consistency in experiments, we considered different turbulence states while keeping the same thermohaline forcing by the melting and freezing.”

- As the reviewer mentioned, we have amended this phrase.

L97: Units missing on Coriolis parameter.

- As the reviewer mentioned, we have added units of Coriolis parameter.

L124: “…was used in whole cases.” Should this be “…was used in all cases.”?

- As the reviewer mentioned, we have amended this part.

L183: Domain center (y=1536m) is different to that stated in Figure 3 caption (y=1728m).

- As the reviewer mentioned, we have amended this part.

L223: Wavenumber is missing units.

- As the reviewer mentioned, we have added units of wavenumber.

Figure 8, Figure 9a: Are units on (rho u v) correct? Should they be kg m^-1 s^-2?

- As the reviewer mentioned, we have amended the units of momentum fluxes in Figure 8, 9a.

L257: “Important to not is that a noticeable trend of heterogeneous patterns of melting rate in the meridional direction is not observed.” I think this sentence is saying that the melt rate is homogenous? But it is a bit unclear, please consider rephrasing.

- As the reviewer mentioned, we have amended this phrase.

Modified phrase:

The heterogeneous patterns of melting rate in the meridional direction (parallel direction to the ice front) are not noticeable.

L259: “Freezing rate” should this be “melting rate” as talking about sub-ice flow?

- We have amended this part with new analysis for heterogeneous freezing pattern.