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The Cryosphere
Discussions

Interactive comment on "Large-eddy simulation of the ice shelf-ocean boundary layer and heterogeneous refreezing rate by sub-ice shelf plume" *by* Ji Sung Na et al.

Anonymous Referee #2

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General comments

This paper has an interesting premise and some potentially significant results, but substantial analysis and revision is required before it can be published. There have been very few LES studies conducted on the ice shelf-ocean boundary layer (IOBL) and I have yet to see one with refreezing included, which makes this work of potentially great interest. However, I am concerned that the set up, validation and analysis of the LES needs considerably more work. I have outlined my major concerns below in the specific comments section, and I would like to see these comments thoroughly addressed.

Specific comments

1. I have concerns about the set up of the LES. The authors describe that the inlet plume boundary condition beneath the ice shelf (and the initial conditions across the whole domain) are set from in situ observations. The in situ observations are measured at the front of the ice shelf, but the inlet plume boundary condition is much further beneath the ice shelf (1000m or so horizontally). According to the authors and the premise of the paper, the IOBL undergoes significant brine rejection, latent heat release and mixing due to refreezing at the ice edge. The resulting profiles of temperature, salinity and velocity in the open ocean are then compared against the same in situ measurements used to force the simulation, to conclude that the refreezing effect is significant.

It does not seem appropriate to force the model with the in situ field measurements (with the inlet forcing at a different region from where the field measurements were taken) and then validate the model against the same in situ measurements (but this time using model results in front of the ice shelf, similar to where the field measurements would have been taken). Perhaps I am missing something in the set up here?

The primary difference between the refreezing and no-refreezing LES depth profiles in front of the ice shelf is then found to be the increase in temperature in the top 400m (Figure 6). I agree that the refreezing case looks closer to the field measurements than the no-refreezing case. But I also question that the initial conditions, and perhaps more importantly the inlet conditions on the plume, have a temperature profile that has values smaller than the average measurement profiles (in particular at 400-550m depth on Figure 6). The authors need to further justify why they have chosen these initial profiles (dashed lines on Figure 6), and any differences that have been made from the field measurements. It is also not clear to me that the solution they have found is truly unique, in that the inlet temperature profile could potentially be tuned to find that the no-refreezing case also gives a good match with the field measurements. I would appreciate a more transparent explanation of the LES set up, including a thorough discussion on the scientific premise going into the set up.

2. I would like to see further validation of the LES in terms of whether it is resolving the dynamics. The authors currently have only one grid resolution here, so further justification to show why they would expect convergence with a higher grid resolution would be appreciated. The LES resolution validation in the paper was solely focused on the energy spectrum. While it is reassuring to see the -5/3 spectrum, there are other variables that really should be considered, in particular the stress, heat and salt flux. Figure 10 already shows the momentum and heat fluxes with the resolved and SGS terms. The SGS terms appear quite small throughout the whole depth, which is a good sign for LES convergence, but I would like to see this compared against the total values for each depth, along with some discussion. Does the salt flux also look resolved throughout most of the depth (especially near the ice)?

3. There are some really interesting dynamics in the LES output but I am struggling to understand them and put them into context of past work. For example, the eddy at the ice front is very intriguing but there is not much information on its dynamics. I did not know whether the authors were referring to a vertical overturning type eddy, or a horizontal eddy. If the latter, is it a baroclinic eddy? What is setting the size of this eddy (e.g. the domain size or a Rossby length scale)? Is the potential vorticity in the under-ice region important in constraining where the eddy forms?

Other dynamics that come to mind are the brine rejection from refreezing. Is the brine rejection enough to generate convective plumes and a convective region? Is this the cause of the mixing in the refreezing zone? I cannot see any brine rejection influence on the salinity field (Figure 3) but this might be hidden by the colormap scale. Is there a density inversion here? Also are there any double-diffusive effects expected in the water column?

What are the effects of the Coriolis parameter in these simulations? Is the horizontal movement of the plume affected by geostrophic balance (is there a strong velocity

in the y-direction)? Would we expect an Ekman layer to form near the ice base e.g. Jenkins 2016 ("A Simple Model of the Ice Shelf–Ocean Boundary Layer and Current")?

In one of the few previous studies on the exit of meltwater plumes from under ice shelves, Naveira Garabato et al. 2017 ("Vigorous lateral export of the meltwater outflow from beneath an Antarctic ice shelf") concluded that centrifugal overturning instability played an important role in setting the mixing of the meltwater plume. Are the present LES similar to these at all?

The paper would be really strengthened by discussing the dynamics in the context of past work. In the introduction in general, I would recommend discussing some more field observations (e.g. Larsen C by Davis and Nicholls 2019, Ronne ice shelf by Jenkins et al. 2010, Fimbul ice shelf by Hattermann et al. 2012, Ross ice shelf by Arzeno et al. 2014) to really put the Nansen Ice Shelf observations into context. Similarly, I think it would be worthwhile citing some more process-based studies here also, especially ones involving a meltwater plume (e.g. McConnochie and Kerr 2018; Mondal et al. 2019).

4. The ice-ocean boundary condition for refreezing is the commonly used "three-equation" model, but how appropriate is this model for the refreezing case (in particular the frazil ice case)? The turbulent exchange velocity of heat is set to be 10ˆ-4 m/s (please provide a citation for this value) but this could be influenced in some way by the refreezing dynamics, including the brine rejection or latent heat release. This three-equation model is parameterising the heat and salt fluxes mixed towards the base of the ice, so I think more discussion should be included to justify the choice of turbulent exchange coefficients. This is a more minor comment, but could the authors define the friction velocity where it first appears (Eq. 14) and also explain how it is calculated (e.g. is a drag coefficient set?).

Li 26: please provide a citation for the line ". . .the ice shelf–ocean interaction in cavities is the dominant driving force for ice thinning"

Li 87: I would also appreciate more discussion of the type of LES used here, and why this type of LES SGS parameterisation would work well in this IOBL system. Has PALM has been used in previous studies of ice-ocean flow?

Li 90: Please describe the turbulence closure scheme used here in more detail.

Eqs. (1-9): Please ensure that all variables are defined when first introduced (e.g. u_g, Rd, Cp not defined here). Also try to include the values of any constants (e.g. what value of Coriolis parameter f is used?).

Eq. (6) and Li 113: are K_m and nu_T the same (they are defined similarly)?

Li 113: citation for C_m= 0.1 and more explanation needed for the definition of l (where does 1.8z come from for instance?).

Is Eq. (13) just the rearrangement of Eqs. (10-12)? If not, where does it come from?

Li 129: please include a citation for the turbulent exchange velocity of heat.

Eqs (14-16): please define friction velocity u* when it first appears. Also is tau the boundary stress?

Li 141: Please justify the surface roughness value of 0.07m. Why was this chosen?

Li 143: How was the ice shelf modeled in the simulations? Was it immersed boundary, interface condition, etc?

Li 150: How was the U_top value chosen? Is it based off observations? If so, please cite.

Li 174: the mean velocity of 0.0729m/s – where did this value come from? Also what is gained by putting the time in terms of the overturning time here?

Li 174: I would like more discussion of the fluctuations – it is mentioned that they are because of large-scale eddies beneath the ice shelf, but it would be nice to see what these eddies look a like a little more in terms of velocity, etc.

Li 177: "High momentum exchange by refreezing and its brine rejection... " please explain the physical processes here a little further. Why does refreezing mean high momentum exchange?

Li 178: The time averaged results of 1t* - why not use a longer time-averaging interval? Especially as the fluctuations appear to be on a slightly longer timescale (Figure 2).

Figure 3 and onward: I have some confusion about zonal and meridional velocity here. For some reason I kept thinking that zonal was the y direction, but actually it was the x direction? Please define the velocity directions in terms of x and y, at least initially. This would help me out a lot!

Figure 3: what are the undulations on the plume interface (top and bottom) on the far left hand side of the domain? Why do they form so strongly near the inlet condition? Are these the eddies referred to in Li 174?

Li 181: What is the swirling strength criterion? Please include a one-line explanation.

Li 182: "Due to neutral buoyancy, sub-ice shelf plume is about 100 m apart from the ice shelf and has a high velocity" This information is important and should come much sooner in the paper.

Li 192: "... where salinity stratification is not formed..." this is tricky to make out on Figure 3 colourmap. Perhaps think of using a different colormap here?

Li 194: "This demonstrates that the stratification is more dominant than flow shear near the ice front and play a major role in preventing flow advection from subice shelf plume." Is this really shown here? Please explain more about what is meant by the role of "stratification" here?

Figure 6: Where were the vertical profiles taken in the LES?

Li 226: "However, the multi-layered stratified characteristics of the salinity profile at depth of ice shelf bottom and IOBL top are observed in the case with refreezing effect."

What is “multi-layered stratified characteristics” referring to exactly?

Li 229: “However, it should be noted that, since this is an idealized model, some differences can be expected between the simulated results and observations, in terms of ice shelf bathymetry and surface roughness, the temporal variability of the sub-ice water plume, the drag effect of frazil ice, etc.” Please discuss these further. E.g. what effects would each of these processes potentially have on the LES?

Li 245: “Additionally, meridional direction-stretched structures are observed at the interface between the inner and outer regions.” Are these referring to the domain-sized undulations on Figure 7?

Figure 8: Is this the vertical heat flux? Similarly in Li 251, “high negative heat flux” is this referring to the vertical or horizontal heat flux?

Around Li 260: So is the supercooled water mixed up from the plume below, or horizontally (by eddy) from waters outside the ice shelf?

Li 263: “Figure 10 shows the vertical profiles of momentum and heat fluxes within the IOBL. As shown in figure, the depth of the IOBL top (438 m) is determined to be the depth where the magnitude of the heat flux is 1% of the maximum heat flux induced by the sub-ice shelf plume.” Is this for the inner or outer region?

Li 265: “In the vertical momentum flux in the inner region, negative flux induced by refreezing and stratification is observed, showing that the IOBL flow in the inner region is in a stable condition.” I thought that there was little to no refreezing in the inner region?

Li 267: “However, positive flux with large-scale advection (IOBL scale) induced by the ice front eddy is observed in the outer region, showing that the IOBL flow in the outer region is in an unstable condition” What about the top 20m where the flow appears to have negative momentum flux?

The flatness factor is of some interest, but I would be more interested to see the energy

budget of the simulations (e.g. turbulent kinetic energy, buoyancy production term, etc). Have the authors thought about calculating the energy budget?

First paragraph of the discussion. This paragraph is a nice description of the overall flow – it might be helpful to have this earlier, in the introduction or the simulation set up.

Conclusions: This should be more to the point, with a succinct summary of the main findings of the paper.

Figures: please consider using different colourmaps for each of the velocity, temperature and salinity figures. It might be easier to follow and make comparisons.

Technical corrections

Li 32: type “groundling” should be “grounding”. Also “. . .dense and salty water melts the ice. . . ”

Li 34: “tidal pumping melts” – what process is this referring to?

Li 39: Please rephrase the sentence “Even iceberg calving . . .” it does not make sense as it stands.

Li 51: “. . . preventing the heat entrainment. . .” Please be clear what heat entrainment is being referred to here.

Li 64: Gayen et al. 2016 used DNS not LES.

Li 105: bracket missing in the fourth term on the RHS.

Li 185: “. . . with negative mean velocity. . .” mean velocity in which direction?

If possible, try not to start all the paragraphs with “Figure x . . .” it is a little clunky.

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