Response to Reviewer

November 28, 2024

Author responses are marked in blue

Comments on: Evidence suggesting frazil ice crystal formation at the front of Hisinger Glacier in Dickson Fjord, Northeast Greenland by Fleur Juliëtte Rooijakkers, Ebbe Poulsen, Eugenio Ruiz-Castillo, and Søren Rysgaard by Sergei Kirillov, Centre for Earth Observation Sciences, University of Manitoba

In this paper, the authors examine an interesting dataset obtained in the marine-terminated glacial fjord in East Greenland and try to characterize the processes occurring at the front of the glacial terminus based on the obtained vertical profiles of temperature and salinity, and also some basic isotopes.

Although I always support the idea of publishing the results of any campaign (especially conducted in the remote hardly or rarely accessible regions), I had mixed feeling while reading the paper. On one hand the presented dataset is worth publishing as it gives an interesting overview of the hydrographic conditions in the vicinity of the glacier terminus that may provide a new insight into the glacier-ocean interactions in the Greenlandic waters. But on the other hand, I was not convinced that the authors presented the confident lines of evidence to support their hypothesis of frazil ice formation near the terminus. My biggest concern is about using a very uncertain heat budget as a main tool to explain the positive anomalies of water temperatures observed within Polar Water layer at the distance up to 40 km from the terminus. The budget that does not include the speeds of inflowing and outflowing waters at different depths.

Thank for your review, Sergei.
We did not include any speed of in and outflow as we only have these available for the outer part (near Ella Ø) of our section. Here we see mostly a flow out of the fjord in the upper 10 m and an inflow below to 50 m. We do not have observations deeper. It is not trivial to deploy ADCPs in front of marine terminating glaciers as they easily get lost to icebergs; for example, a mooring deployed in Dickson Fjord was lost under such conditions.

From my point of view, the observed anomalies have nothing to do with the frazil ice at all. My logic is: if the formation of frazil ice results in releasing latent heat that increases the water temperatures up to 0.5C within ~40-100m layer up to 40km away from the glacier, the melting of this frazil ice near the surface must lead to the opposite effect and results in consuming some (atmospheric) heat from the surface 0-10m layer. As a result, the surface layer temperature within that 40km range should be roughly 3C (=0.5C * (100m-40m) / 10m) lower than beyond 40km limit. However, we see nothing like this, but even opposite – the heat content of the surface layer within 0-40km segment is larger than further down in the fjord.

Not necessary. The atmospheric temperature in the bottom of the fjord is ca 2°C warmer than further out fjord (local meterological observations from GIOS-lite). So the heat flux from the atmosphere is not constant along the section.
We agree though that it is still unclear how far out the frazil ice will survive before melting. The heat from frazil ice formation, however, will be released close to the glacier where freshwater is released. The melted frazil ice will be visible in the isotopic data outfjord eventhough it is melted. The temperature due to frazil formation will stay in the polar water layer, but the salinity signal will be absent as we cannot measure freshwater within frazil ice with a CTD . However, when the frazil rises and reaches higher temperatures, it will melt and can therefore be measured at the surface (above 0°C). We would indeed expect an uptake of heat around 0°C when the crystals encounter positive water temperatures. As can be seen in the 0°C isotherm in Fig. 5, this melting line tends to be higher towards the bottom of the fjord (<40km from the terminus) compared to further out fjord (>40km from the terminus), indicating some cooling effect is occurring around this line further in-fjord.
We will replot Fig. 4 in the manuscript so this is more clear.

In Loewe (1961) paper (On melting of fresh-water ice in sea-water), the fast dissolving of the large chunks of fresh ice in salt water with negative temperatures (but 0.15C above freezing point at given salinities) was demonstrated. Even if one suggests that plenty of frazil ice crystals form at the boundary where fresh subglacial discharge meet cold Polar Water, what is a chance they survive long out of the subglacial plume next to the terminus wall? While the crystals stay within the plume with zero salinity and zero temperature, they don't melt or dissolve. But once they drift to the salt water with temperatures above freezing, these small crystals will dissolve instantly (not as shown in Fig.7). Therefore, all these frazil ice processes (including a potential latent heat release) are likely occurring within a very limited distance near the glacial terminus and, from my point of view, can't affect the water column at tens of kilometers away from the glacier.

Mortensen et al. (2020) observed subglacial freshwater (from subglacial plumes) at eleven kilometers from the terminus. This indicates that frazil ice may reach farther distances than just a few meters from the terminus. However, we still expect that the majority of frazil ice processes occur close to the glacier terminus, as you also suggested. We will adapt this in the schematic of Fig. 7 so it shows the frazil ice crystals closer to the terminus.
We have made photos of frazil ice using a new profiling method (based on polarized light) 200 m from the glacier front and at Ella Ø this summer. We find frazil in front of the glacier and not at Ella Ø. This will form the basis for further investigations during a PhD for Fleur (first author). Thus, we will deal with this in more details on different glacier types during the next 3 years in her PhD.

The second big concern is related to the suggestion that there are 3 oppositely directed flows within the upper 10m layer as presented in Fig.7. Please see my comment to Line 194 for more details.

We answer your comment below.

There is also a small general concern about attributing Dickson Fjord to the northeastern part of Greenland. I don't know where the center mass of Greenland is, but its latitudinal span from 59N to 83N gives the center at 71N. From this perspective, the position of the fjord at 72N is at the east of Greenland, not northeast.

Point taken – we call it East Greenland.

Below is the list of other (mainly minor) concerns that need to be addressed:

Line 16: A significant portion of GIS mass loss (88% (Mortensen et al. (2020))) can be attributed to melting at the front of marine-terminating glaciers (Straneo et al. (2012))

It's not clear why two references are separated and what each reference is attributed to. If Mortensen et al. found exact number, why do you need to include Straneo et al.?

We will remove the reference by Straneo et al 2012.

Line 20: Along with the increase in surface melt, the interaction of deeper warmer Atlantic Water masses with the glacier terminus has been found to increase submarine melting (Straneo et al. (2012); Zhao (2022); Holland et al. (2008)).

Submarine melting is also a "surface" melt. Just on the vertical surface. Wouldn't it be better to specify that surface melt means the melt at the top of the glacier or use supraglacial discharge term?

We will rewrite to: Along with the increase in supraglacial melt, the interaction of deeper warmer Atlantic Water mass with the glacier terminus has been found to increase sub-surface melting (Straneo et al. (2012); Zhao (2022); Holland et al. (2008)), further contributing to GIS mass loss.

Line 30: Change "glacier front" to "glacier terminus".

Corrected as suggested.

Line 36: These findings contribute to ongoing efforts to accurately model and predict the impacts of glacial meltwater on the coastal region, ecosystem dynamics, and global sea-level rise.

The paper is focused on the frazil ice idea. I don't think it is somehow contribute to the global sea-level rise problem.

Sentence will be changed to: 'These findings contribute to ongoing efforts to accurately model and predict the impacts of glacial meltwater on the coastal region and its influence on ecosystem dynamics.'

Lines 43-44: Repeating information that was already presented in the Introduction.

We will remove the repeating text.

Line 65: An oceanographic mooring device

"Device" is needless here.

We will remove it.

Line 75: Hydrographic sections of temperature, salinity, density and stable water isotopes were generated with a resolution of 1000 cells in both distance and depth directions.

Mentioning the method of interpolation would be more essential than giving the grid size.

Suggestion followed, the sentence now reads: 'Hydrographic sections of temperature, salinity, density and stable water isotopes were generated by linearly interpolating the data, with a resolution of 88 metres along the horizontal distance and 0.3 metres along the vertical depth.'

Line 121: Profiles, not transects! The insets in Fig.2 could be larger for better showing the observed anomalies (especially for salinities), I think. The size of empty space in the main panels allows this. There is an impression that the freshwater freezing line in the left panel of Fig.2 is above 0 at the surface that can't be right.

'Transects' will be changed to 'profiles'. In Fig. 2 the insets have been made larger and the Freshwater freezing line has been fixed.

Line 129: "depending on the distance and location with respect to the glacier terminus".
You may be more specific (for the Results) by saying that temperatures generally decreased off the terminus and the salinities increased. The sentence inLine 131 ("Interestingly, the transects show an increase in temperature in the Polar Water layer closer to the terminus") is needless in this case.

Suggestion followed, the sentence will now read: 'The underlying Polar Water layer has low temperatures below the freshwater freezing point, ranging from -0.8°C to -1.7°C, and salinity values of 31.8 to 32.1, with temperatures decreasing and salinity increasing as the distance from the glacier terminus increases.'

Line 133: "subaqueous surface melt"

Melt of what? If a glacier terminus is 0C, it won't melt is seawater is above in-situ freezing point of, for example, -1C. The glacial ice will dissolve, but it's a rather different process. If you consider GLACIER (zero salinity) MELT, you have to change "when ambient seawater is above the pressure-salinity-dependent freezing point" as follows: "when ambient seawater is above the pressure-salinity-dependent freezing point".

Here the "surface melt" is used in relation to the vertical surface of the terminus, whereas in Line 20 the authors used this term for the melt at the top of the glaciers.

Thank you for pointing out this inconsistency. We will change 'surface melt' in line 20 to 'supraglacial melt' to avoid confusion.

And it's better to replace "subaqueous surface" with "sub-surface".

Suggestion followed.

Line 148: "colder values"

Change to "colder water" or "lower temperatures"

Suggestion followed, changed to 'lower temperatures'.

Line 148: "The Flights 1-3 values from the drone-deployed CTD interestingly exhibit colder values at salinities below 18, with the temperature staying relatively constant as the salinity increases up to 26, compared to warmer freshwater becoming colder with salinity at the stations 1 and 2 relatively nearby."

The sentence is difficult to follow.

The sentence will be rewritten to: 'Interestingly, the drone-deployed CTD measurements from Flights 1-3 show colder temperatures at salinities below 18 than the measurements conducted further away from the glacier terminus. The temperature of the flight measurements remains relatively constant as salinity increases up to 26. This pattern contrasts with nearby Stations 1 and 2, where warmer and fresher water cools as salinity increases in this range.'

Line 151: "A runoff slope was plotted in Fig. 3 to investigate runoff mixing. Thermal satellite data showed that surface waters are released with a temperature of approximately 4 ◦C"

The authors should go through all the text and carefully check all used terms and different combination of terms. For example, what does "runoff" attribute to here? Coastal runoff? Runoff from the surface of the glacier? Subglacial runoff? What does "surface waters are released" mean? Released from where? There are quite a few confusing places like this in the text.

Suggestion followed.

Lines 153-155: The plotted "runoff slope" is also a mixing line. Why do you attribute the last term to the subglacial discharge only? Also, in "a 'mixing line ... represents the line connecting the deeper water body..." what the deeper water body is? From the left panel, it looks like as the deepest level at stations 1-2 or ~170m (Fig.2), is it? Please specify, that this is the depth that approximately corresponds to the draft of the tidewater glacier. If you do so, it will be easier to understand the following sentence: "Therefore, the presence of subglacial discharge in the deeper water body is unlikely."

We will change the name of the 'runoff slope' to 'surface glacier runoff slope', and the 'mixing line' to 'subglacial discharge slope'. We will also specify that the depth approximately corresponds to the draft of the tidewater glacier as suggested.

Line 156: "From the meltwater slope plotted in Fig.3".
There is no such line in Fig.3. There are "runoff slope", "mixing line" and "surface freezing line". Please, be more consistent with the terminology you use and choose it carefully.

Consistent with the name changes of the lines in Fig. 3, we will adapt this sentence to: 'From Fig. 3 we see that points do not fall along the subglacial discharge slope, making the presence of subglacial discharge in this deeper water body unlikely.'

Line 158: "In Flights 1 and 2 data, however, the slope changes from positive to negative in the salinity range 24-28. This slope becoming positive can be attributed to meltwater influx, as these lines change direction towards the subglacial discharge point (θ, S) = (0 ∘C, 0). Interestingly, in Fig. 3, a slope change occurs in the lower salinity waters, with the lowest salinity water slope parallel to or even steeper than the runoff slope."
This is very unclear. Slope of what? If it is what I understood, I see no slope change between 24-28. It is still negative at both <24 and >28. You probably meant a positive anomalies of temperatures within this range of salinities? And again, what does meltwater influx mean? From the surface? Subglacial? Coastal? What does "these lines change direction" mean?

The text will be changed to: In the data from Flights 1 and 2, the data points fluctuate within the salinity range 24-28, alternating between positive and negative slopes. This fluctuation may be linked to subglacial meltwater influx, as the trend shifts direction (leading to a change in the slope) toward the subglacial discharge point (θ, S) = (0 °C, 0). This shows a change in the temperature and salinity in response to meltwater input.

Line 163: "To increase spatial distribution over the observed differences"

I don't think "increase" is a good word here. Maybe "to examine the spatial patterns of T, S, D in more details"? Figure 4 needs station marks showing the dates of different stations in different color. There had been up to 2 weeks interval between different CTD casts. I would also think of adding few isotherms between -1 and -1.5 (-1.3 an -1.1 for example) to the PW layer temperature panel. It will emphasize the gradual increase of temperatures toward the glacier.

Suggestions followed

Line 166: Why do you use “contour plot” here and “sections” for T/S/D earlier?

We will change ‘contour plot’ to ‘sections’ for consistency.

Line 175: “Interestingly, this deeper signal becomes (slightly? as compared to the depletion in the surface layer) more depleted further from the terminus”.
Line 183: “Below this decrease, a second depleted signal was found at around 10 m depth, which no longer would include glacial runoff to the surface ocean, but due to the positive ocean temperatures can still be caused by surface melt (Fried et al. (2018))”

I found it difficult to understand what is a role of ocean temperature in forming this depleted layer.

We will make this to appear more clear. The depleted isotope layers in the surface may be caused by the ice mélange in the surface moving under the influence of wind and tide. The lower depleted isotope layer originates from frazil ice melting of crystal rising from subglacial discharge. In between these two layers could be the winter layer as you suggest below.

The sentences have been reformulated to: Line 175: “Interestingly, this deeper signal becomes slightly more depleted further from the terminus”.
“Below this decrease, a second depleted signal was found at around 10 m depth. This depletion could be attributed to subsurface melting caused by positive ocean temperatures in contact with the terminus (Fried et al., 2018) or by melting frazil ice formed from the refreezing of subglacial discharge, or a combination of both. The frazil ice crystal processes will be explained in more detail in Chapter 3.4.”

Line 187: “...there is still a depleted water signal distinguishable in the Polar Water layer. While this meltwater signal could be attributed to subglacial discharge, the salinity profile does not show a corresponding freshwater signal”.

Are you talking about Polar Water near the glacier terminus? Because if so and if the inset panels in Fig.2 were larger, it would be easier to see that PW water near the glacier is slightly fresher (the depleted dO18 signal is not very strong either!).

Though there is a slight decrease in salinity closer to the terminus, this does not correspond to a depleted water signal, as the water isotope values actually become more depleted further from the terminus (thus we should expect a more saline signal corresponding to this historic meltwater). This interesting discrepancy has been further emphasized by adding more contour lines to both the salinity and the water isotope sections.

Line 194-199:

I don’t find this explanation very convincing. First of all, I can hardly accept the idea that the difference of T/S/dO18 observed within upper 10 meters is related to the classic estuarine circulation in fjords. Of course, the current velocity data (from the mooring?) would help to examine this theory, but I would suggest a slightly different scenario.

As stated previously we do not have current mooring data inside the fjord close to the glacier since we are in new territories, and these are challenging to deploy.

What if the entire 0-10m low-salinity surface layer is formed at the end of winter because of sea ice melt. Later in the summer season, it gets heated up to 9-10C and, at some point, starts to receive the dO18 depleted water with zero salinity discharging from the top of the glacier (or maybe from the land). This depleted water could explain the signal at 1m. What is happening below 10m is the PW that flows toward the glacier at 50-75 m (see Fig.4 temperature panel. Adding -1.3C -1.1C contours to that panel will help to better visualize this I believe). This water mixes with subglacial discharge and upwell towards the surface. However, at ~10m depth it meets the strong density interface and spreads off the terminus giving that depleted subsurface tongue at 10m. For me, this scenario looks more realistic than your idea of an opposite estuarine circulation (with 3 oppositely directed flows!) between 1 and 10 m depths.

If PW should reach the glacier at 50-75 m should mix with subglacial discharge and upwell to the surface we should also see a signal in salinity! We do not observe that (Fig. 4 and Fig. 6). Our interpretation is that frazil ice crystals cannot be observed in a traditional CTD, but temperature released due to freezing can! We would like to keep our explanation as it is.

However, we like your idea with the winter layer and have used it to explain the layer between the surface depletion and the depletion caused by rising frazil ice, which we have already described in lines 189–192. As we do not have evidence for a three layer flow we will delete the middle inflowing arrow in Figure 7a, as well as the accompanying explanation.

I would strongly recommend to show the SW part in Fig.6. If the scenario I suggested is correct, we may see some positive thermal signal at ~10-20 meters that spreads off the glacier.

We did not include the SW part in Fig. 6 due to the difficulty of defining a reference temperature in this layer. Unlike the Polar Water layer, where the minimum temperature at that depth serves as a baseline, surface temperatures vary widely (due to differences in atmospheric input across the fjord), making it impossible to determine a reliable reference value for this layer.

Line 273: “temperature and salinity” are not used in the formula (4)

Corrected

Line 277: I think the radiation was measured not at the sub-surface mooring, but at the coast.

Corrected

Line 287: "Subtracting these values from the incoming radiative heat flux"

Was air temperature below surface water temperature in August? Because if not, one needs to add sensible heat flux to the surface energy budget, not subtract.

We will revise the calculation, so the sensible heat flux direction is based on whether air temperature is above or below the surface water temperature.

Below are my answers to some specific questions the reviewers are supposed to address
Does the paper present novel concepts, ideas, tools, or data?

The paper accommodates a piece of novelty related to using of a new drone-driven CTD in the vicinity of glacier terminus. However, the majority of data used to build the story is related to the standard measuring oceanographic techniques. Although the basic idea of attributing the anomalies in water temperatures to the frazil ice formation is interesting (but not new according to the authors), the lines of evidence don't look 100% convincing without more detailed and specific observations (i.e. accumulation of frazil ice in front of glacier in winter time, current velocity measurements for estimating Polar Water residence time in the fjord, or something else).

Are the scientific methods and assumptions valid and clearly outlined?

Mostly yes, although there is some unclarity in terminology that has been used in the different parts of the paper. See my specific comments above. From my point of view, the most problematic part in the paper is 3.5. I honestly tried to get through it but failed. The authors should consider put some additional efforts for making this chapter clearer and easier to follow. A combining heat fluxes (within specific period of time) with the observed heat storage in the water (without knowing the history of that water and its residence time in the local system) is a very tricky game.

We will adapt the terminology throughout the paper to be more clear and consistent, as suggested. We see that chapter 3.5 is challenging to follow due to the extensive description of the calculations. To improve readability and structure, we will separate the text based on the quantities being calculated.
We agree that it is tricky to estimate heat flows without knowing the water movement and history. As already mentioned in the conclusion, understanding these in- and outflows is essential to confirming our hypothesis. However, the current estimates represent the best we could achieve with the available data. We will include an additional note discussing the limitations of our calculations.

Are the results sufficient to support the interpretations and conclusions?

I don't think the presented results are sufficient to support the main hypothesis about the presence of frazil ice. At least in quantities that would explain the observed positive thermal anomalies within Polar Water layer up to 40km away from the glacier.

With the changes made to the paper after the review, particularly the updated title, we aim to have (partially) shifted the scope of the paper. The focus is on meltwater from the Greenland ice sheet and its water isotope distribution in Dickson Fjord, the frazil ice crystal hypothesis serves as a potential explanation to (partially) account for the observed heat in the Polar Water layer, offering an interpretation of the somewhat surprising hydrographic results. As mentioned, photographs of frazil ice crystals taken in the fjord will be included in a future study to provide more evidence.

Does the title clearly reflect the contents of the paper?

Yes, although the content of the paper didn't convince me that the main result shown in the title is correct.

Does the abstract provide a concise and complete summary?

Yes.

Is the overall presentation well structured and clear?

The structure of the paper is fine, but the authors need to carefully revisit the terminology related to the different portions of the glacial discharge and melt.

References

Mortensen, J., Rysgaard, S., Bendtsen, J., Lennert, K., Kanzow, T., Lund, H., & Meire, L. (2020). Subglacial discharge and its down-fjord transformation in West Greenland fjords with an ice mélange. *Journal of Geophysical Research: Oceans, 125*(9), e2020JC016301. https://doi.org/10.1029/2020JC016301