Point-by-point reply

We again take to opportunity to thank the reviewers for insightful and constructive comments.

We have revised the paper following closely the response to the reviewers' comment that we posted in the on-line discussion. We will first describe how we have addressed some of the more substantial comments; our response to the detailed comments are listed below.

Subglacial discharge

In our conceptual model, we assume that the freshwater input due to subglacial discharge is small compared to the freshwater input due to subsurface ice melt. Both reviewers point out that this assumption is not generally valid for tidewater glaciers, and ask for a discussion of this point.

In response, we have added a new appendix (including a new figure) that derives the conservation relations presented in section 2.1 accounting for subglacial discharge. The appendix shows that the model results presented in the paper hold qualitatively also when the freshwater input due to subglacial discharge is large compared to the freshwater input due to subsurface melt. The regime of tidewater glaciers with high subglacial discharge deserves a separate study, but the present results should give some qualitative guidance of how hydraulic control affects subsurface melt dynamics also in this regime.

In the beginning of section 2, we refer to the results of the new appendix and also point to observational evidence suggesting that the limit of neglecting subglacial discharge can be a reasonable leading-order approximation for large Greenlandic ice tongues such as 79°N, Petermann, and Ryder.

We have also added a few sentences in section 3.2.5, stating that the case $n_1 = 1$ and $n_2 = 0$ may be relevant for tidewater glaciers. This statement is also included in the caption of Fig. 10.

Information on fjords and glaciers: Figure 2 and 3

The reviewers asked for some additional information on fjords and glaciers, particularly about 79°N, and offered suggestions for improving Figs. 2 and 3.

In response, we start section 1.1 by giving some general facts concerning Petermann, Ryder, 79°N glaciers in North Greenland, and point to papers that describe 79°N (e.g. Wilson et al., 2017; Lindeman et al., 2020; Schaffer et al., 2020), before we begin the comparison between Ryder and Petermann. We have also marked the location of 79°N in Fig. 2a.

For readability of Fig. 2, we decided to not indicate the positions of the CTD profiles shown in Fig. 3. In the caption of Fig. 3, we refer to Jakobsson et al. (2020) and Stranne et al. (2021) – where the positions of the CTD stations are given – and also refer back to Fig. 2 giving in words approximate positions of the stations.

We have revised Fig. 3 to indicate the vertical extents of the model's layers and sill depths for Petermann and Ryder.

Minor comments reviewer 1

L14 – the use of "marine ice" – I worry that this terminology could be a bit confusing. I'd suggest rephrasing using "marine-terminating glaciers".

We have revised as suggested.

L26 – Slater et al., 2022 recently argued that for some regions, the impact of increasing subglacial discharge on submarine melt has been as important as AW temperature – could be worth acknowledging here.

We have reformulated: *In Greenland, basal melt is sensitive to the AW temperature (Straneo and Heimbach, 2013), and increases in AW temperature and subglacial discharge have been the major drivers of the retreat of outlet glaciers in deep Greenlandic fjords since the mid 1990s (Wood et al., 2021; Slater and Straneo, 2022).*

L32 – "can stabilise marine glaciers" – I feel this statement is too certain for this point in the paper. Perhaps "has the potential to stabilise marine glaciers"?

We have revised as suggested.

L34 – either here or somewhere else appropriate, I think it would be worth acknowledging that processes other than hydraulic control can also modify AW between the shelf and the glacier – for example vertical mixing due to velocity shear even in the absence of a sill, or icebergs.

We have reformulated in the following way: *Numerous observations of sill flows demonstrate that the vertical mixing increases strongly when the flow becomes hydraulically controlled (Pratt and Whitehead, 2007), and Jakobsson et al. (2020) and Schaffer et al. (2020) show that as inflowing AW passes over the sills and descends on the landward slopes, it mixes with overlaying cold glacially-modified water.*

Fig. 2, panels b and c – it would be great to have a scale bar for these panels.

We have included scale bars.

Fig. 3 – it would be great to have the locations of these profiles shown on Fig. 2b and 2c

For readability of Fig. 2, we decided to not indicate the positions of the CTD profiles shown in Fig. 3. In the caption of Fig. 3, we refer to Jakobsson et al. (2020) and Stranne et al. (2021) – where the positions of the CTD stations are given – and also refers back to Fig. 2 describing approximate positions of the stations.

L78 – it would be nice to finish off the introduction with a sentence that bridges into the next section. For example, "We now describe a two-layer model to investigate .."

We have done as suggested.

L122 (and a few other places) – it would be more consistent to refer to "Eq." instead of "relation"

We have followed this suggestion.

L129 – is the value of rho0 ever actually used in the model? Or does the density difference always get normalised by rho0 (e.g. Eq. 22), in which case there would be no need to assume a value for rho0.

This is correct, and we simply write "where ρ_0 is a constant reference density ..."

L198 – I don't quite follow why the exchange flow increases with deltaT when $n_1 - n_2 > 1$. From Eq. 21, don't we require $n_2/(n_1 - n_2) > 0$? Which would give $2n_2 - n_1 > 0$, but perhaps I am mistaken.

We have assumed that $n_1 \geq 0$ and $n_2 \geq 0$, but did not state that clearly. When $n_2 \geq 0$ it is simple to see that $n_1 - n_2 > 0$ is the relevant criteria. We now state that $n_1 \geq 0$ and $n_2 \geq 0$ when the exponents are introduced.

L200 – I think somewhere in this paragraph it would be appropriate to cite Zhao et al. (2021), which similarly looked at parameterising hydraulically-controlled transport (e.g. Eq. 17 in that paper).

This paper is very relevant. We cite the paper around L200 and also on L45.

Fig. 4 – could you say how the axes are non-dimensionalised?

The axes are non-dimensionalised such that the AW height is one when the AW thermal forcing is one; we will state this. Equation (28) shows that non-dimensionalisation can be done by selecting an arbitrary scale for the AW thermal forcing ($\mathcal{T}_A$), and then define a non-dimensional h that is one when non-dimensional $\mathcal{T}_A$ is one. This information is given in the figure caption.

L315 – suggest adding "in the case n1=2 and n2=1" at the end of the first sentence

Done.

Figs. 6 and 7 – it could be better not to use the jet colorscale

We think that this is partly an aesthetic matter, and the jet scale is preferred by a color blind coauthor.

Fig. 12 caption – "see the text for details" – did this mean to look at the text for details on the refreezing, or for details on the figure more generally? I took it to mean details on refreezing, and I think I didn't see those, so perhaps revise.

We have revised the figure caption to make this clear.

L492 – suggest adding "unmodified" before "AW".

Done.

L506 – on the two idealised scenarios – can you speculate which might be more realistic? Scenario 2 feels more realistic to me because there is more a gradual transition from no entrainment to some entrainment, but perhaps we are not able to say yet.

Scenario 1, which assumes no entrainment, is extreme and less likely: the observations from Ryder and 79N show that entrainment occurs. Thus, scenario 2 is more realistic. This is also supported by the paper of Bao and Moffat (2023), which has recently been published in Cryosphere Discussion. They report an ocean-modelling study of glacial melt in a silled fjord, and their results support scenario 2. We state this around L506 and also in in the beginning of section 3.

L536 – on Ryder and 79N having "basal melt processes that are less sensitive to thermal forcing than Petermann" – surely according to your model, the basal melt processes at all of the glaciers are equally sensitive to thermal forcing (because M varies as T^{n_1})? So is the higher melt rate at Petermann likely due to factors beyond thermal forcing (i.e. gamma1 in your equations), such as subglacial discharge or grounding line depth or basal slope?

Good point! We have changed to: "*basal melt processes characterised by lower thermal sensitivity coefficients γ_1/A than Petermann*".

L538 – suggest adding "at 79N" after Schaffer et al. (2020)

Done.
Typos etc
Corrected.

Specific comments and typos, reviewer 2

L.18 - Basal melt relates to the melting occurring at the base of an ice body (either grounded or floating). However, basal melt here only refers to the floating part of the ice (ice shelves and ice tongues), but it doesn't to tidewater glaciers with vertical ice front, which are also marine-terminating glaciers.
We have changed to subsurface melt.
L.19 – The definition of grounding line given here is only valid for ice shelves and ice tongues. The grounding line feature is also present in tidewater glaciers with a nearly-vertical ice front, where no permanent floating ice exists.
We now write: "the point where the ice begins to float (or for tidewater glaciers, the water depth at their essentially vertical fronts)".
L.20 – The effects of water column stratification on submarine melting was also reported on De Andrs et al. (2020).
The paper is cited here, and on L290.
L.46 'effects due Earth's rotation' – 'effects due to Earth's rotation'.
Done.
Section 1.1 - As stated in L.52-53: 'the model results are discussed in relation to observations from... and 79N glacier'. However, no information of the physical settings of 79N glacier is provided within the whole manuscript. Is there any reason for this lack of information?
We start section 1.1 by giving some general facts concerning these three ice tongues in North Greenland, and point to papers that describe 79N (e.g. Wilson et al., 2017; Lindeman et al., 2020; Schaffer et al., 2020), before we begin the comparison between Ryder and Petermann.
- In order to contextualize the rate of frontal advancing/retreating and get a frame of reference for the sill influence on hydraulic control, could the author specify what the lengths and widths of these two glaciers and fjords are? and the depth range of the grounding lines and ice-tongue fronts? I can only found GL and front details for Ryder glacier in Fig.2 caption.
We now provide most of the information the reviewer asks for in the beginning of section 1.1, and in the captions of Fig. 2 and 3.
L.57 - It would be better to quantify 'a relatively deep and wide sill'.
We now write: 'a ∼400 m deep and ∼12 km wide sill '.
Fig.2 - In panel a), it would be nice to have the coordinates frame and the North arrow.
- In panels b) and c), a scale bar (and a more precise bathymetric colorbar) would help with the fjord and sill dimensions. It seems that the coordinate 630'W appearing on the left y-axis of pannel b) is a mistake. It would also be helpful to have in these pannels (b and c) the location of the CTD casts used in Fig. 3.

Figure 2 has been revised as suggested; but the CTD stations are not shown.

L.80 and 86 - Based on CTD observations, it would be helpful to give a thickness range of the two layers considered in the model, as well as the thickness of the surface-polar-waters layer (it could also be highlighted on Fig.3).

We have revised figure 3 to indicate the vertical extents of the model's layers.

What are the limitations on the study (if any) of avoiding mixing between glacially modified and surface polar waters?

The important model constraint is that glacially modified does reach and mix with near surface waters that receive a strong input of surface runoff, as this freshwater source is not included in the model. Some mixing between glacially-modified plume water and the layer of surface polar water is expected to occur. This will cool and freshen the outflowing waters to some extent, but this process is neglected for simplicity. We have not addressed this point.

L.82-83 - What are the limitations of neglecting subglacial discharge as a mechanism enhancing basal ice-tongue melting?

The main effect of subglacial discharge that is comparable to or larger than the basal melt is that Eq. (10) in the paper – the relation between the difference in salinity (ΔS) and the temperature (ΔT) between the two layers – becomes modified and depends on the subglacial discharge. Essentially, ΔS will for a given ΔT be larger than predicted by Eq. (10). This strengthen the layer density difference and causes the transition into the hydraulically-controlled regime to occur for somewhat greater sills heights than in the limit where subglacial discharge is neglected in the freshwater budget. We have included a new appendix that describes some qualitative effects of finite subglacial discharge; see response above.

L.82-83 Table 1 - Last row, in Gade temperature relation, change the 'equal symbol' by the 'almost-equal symbol' (as it appears in L.111 and L.116). Also, I am a bit confused, since it seems to be inconsistencies with the magnitude and units of this Gade temperature. A value of 80 K is given in Table 1 (which is consistent applying the proposed relation therein), but a value of 80 C is given in L.111. From other studies (e.g. Jenkins, 1999; Mankoff et al., 2016), this Gade temperature values are about -90 C. Could you, please, unravel this question?

The equivalent ice temperature used by Jenkins (1999) is essentially $-T_G \cdot \frac{\rho_w}{\rho_i}$; where the factor ρ_w/ρ_i emerges because we use unit volumes of liquid water in the definition of T_G. We state this in the text. To avoid possible confusion related to the use of both the Kelvin and Celsius temperature scales, we use only Celsius. Also, we use the following slightly more accurate numerical values $L/c \approx 75$ °C and $T_G = L/c + c_i/c(T_f - T_i) \approx 80$ °C (where the ice temperature $T_i = -15$ °C).

L.111 - Modify L/c value/units according to my previous comment.

We have done this using °C.

L.198 - 'This show the' → 'This shows that the'

Done.

L.204-205 - Could also a significant subglacial discharge flux motivate this subcritical-to-critical transition? Answered in L.272-273.

OK.

L.206-207 - See also Hager et al. (2022), where a simple model is used to estimate the proportion of refluxed freshwater in a silled fjord and the potential impacts on submarine melting are discussed.
We cite this paper in the beginning of section 3.2.1.
Foot note 1 - The word 'than' is repeated twice in the second line.
Done.
L.245 - Shouldn't it be $R < 1$ in the hydraulic regime, since $R = 1$ is reserved for the melt-controlled regime?
Done.
Fig.4 - What are the h and deltaT used to make axes non-dimensional?
We explain the non-dimensionalisation in the caption.
L.289-290 - Increased stratification generated by strong surface melting has also been observed to dampen submarine melting in tidewater glacier-fjord systems (De Andrs et al., 2020).
We cite this relevant paper.
L.292 - 'The reasoning above and suggest that' → 'The reasoning above suggests that'.
We have corrected this.
Fig.8 - in L.3, 'is smaller (greater) than one the hydraulic' → 'is smaller (greater) than one in the hydraulic'.
Done.
L.446 - I understand the near-bottom temperatures for the ice cavity, to get better estimates of those temperatures near the grounding line, but, shouldn't outside-forced temperatures be those at the near-sill depth, where the flow exchanges are taken place?.
Figure 3 shows that the near bottom temperatures outside the sills, which characterise AW temperatures, are essentially equal to temperature at the sill depth. We have rewritten to make this clear.
L.460 - Please, quantify 'with large error bars'. We removed 'with large error bars' as there is difficulty to provide such from measurements taken at one particular time. Instead we write: ' to be on the order of $50 \cdot 10^3$ m^3 s^{-1}.'
Fig.11 - in L.2, 'and 79' → 'and 79N'.
Done.
Fig. 12 - To get a more comprehensive understanding, it would be nice to have the squares for the three glaciers, not only for the Ryder glacier.
Regrettably, this is not possible as the basal melt shown in Fig. 12 is based on the Ryder model parameters. Separate figures are needed to show the other glaciers, and we decided to present only the Ryder case.
L.490 - 'Our results suggests' → 'Our results suggest'.
Done.
L.521 - 'longer that today' → 'longer than today'.
Done.

References

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