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Interactive comment on "Linking catchment-scale subglacial discharge to subsurface glacially modified waters near the front of a marine terminating outlet glacier using an autonomous underwater vehicle" *by* L. A. Stevens et al.

Anonymous Referee #1

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General comments

This novel paper presents hydrographic measurements from a fjord in west Greenland, collected partly using an autonomous underwater vehicle. These measurements are unique in their detail and proximity to a tidewater glacier. By comparing to inferred subglacial hydrological pathways, the authors are able to qualitatively match glacially modified water in the near-ice fjord with estimated subglacial discharge channel locations. The paper offers constraints on the pattern of subglacial discharge emerging at the grounding line of the glacier, constraints which are difficult to obtain but much

needed for understanding of submarine melt rates and glacier dynamics. Given the unique nature of the data presented, the clarity of the paper, and the interesting implications for ice-ocean interactions, I believe this paper is suitable for publication in The Cryosphere provided that the (mostly minor) concerns below can be addressed.

Specific comments

Main concerns

One concern lies with the geometry of the plume model used, which I believe is inappropriate here. The authors use a line plume model (Jenkins, 2011) which assumes a uniform distribution of subglacial discharge across the grounding line. In particular, if this line plume has parallel-to-grounding line width w and perpendicular-to-grounding line width h, use of the equations presented in Jenkins 2011 requires $h \ll w$, as entrainment at the plume sides is neglected. In this paper the subglacial discharge is assumed to emerge through Röthlisberger channels which have $h \approx w$ at source. Therefore a point source plume model (e.g. Morton et al., 1956; Carroll et al., 2015; Cowton et al., 2015) would be more appropriate. Indeed use of a point source model will result in greater entrainment which may improve quantitative agreement between the data and plume model. Use of a point source model would also avoid the need for the rather contrived argument (p4599 lines 20-22 and p4600 lines 3-6) needed to match Röthlisberger channel discharge with line plume initial conditions. I don't expect that use of a point source rather than line plume will change the qualitative results nor the conclusions of the paper, nevertheless I think it is important that a point source plume should be used when point source discharge is assumed.

My second main concern is that a little more discussion could be allocated to the region between D1 and D2, where the authors indicate there is "little to no subglacial discharge". It would, for example, only take ~0.02 m^2/s of discharge distributed across the grounding line between D1 and D2 (~3 km) to account for ~50% of the total discharge from the glacier. Given that the fjord is quite weakly stratified at depth even this small discharge might lead to significant submarine melt, e.g. Sciascia et al., (2013). I understand that it is probably impossible to say much more on this issue from your data but if this paper wishes to provide constraints on subglacial hydrology for submarine melt modelling then I think a slightly expanded discussion along these lines should be included. The line in the abstract on this point might also be scaled back (maybe remove "only" from line 13?)

Lastly the discussion relating plume theory to the differing properties of GMW1 and GMW2 (p4601 line 27 – p4602 line 23) appears rather confused and needs correcting. Firstly, in p4602 line 9 the authors state that an increase in subglacial discharge leads to "a decrease in the fraction of subglacial discharge in the plume". I don't think this is true (and indeed this statement appears at odds with similar statements in p4596 line 16 and p4602 line 21). According to Straneo and Cenedese (2015) Eq. 8, for a line source plume volume flux scales with the initial buoyancy flux B raised to the power 1/3. Subglacial discharge itself scales with B. Therefore the fraction of subglacial discharge in the plume scales with $B/B^{1/3} = B^{2/3}$, meaning that the fraction of subglacial discharge in the plume increases as subglacial discharge is increased. So although it is true that large subglacial discharges drive higher entrainment fluxes, the increase in entrainment ($B^{1/3}$) is not as large as the increase in subglacial discharge (B). This observation also affects p4602 lines 15-16 and lines 17-18. Furthermore the contrast in properties between plume and ambient also scales with $B^{2/3}$ (Straneo and Cenedese (2015), Eq. 8, expression for g') therefore plume temperature is decreased as subglacial discharge increases. Finally the authors state that "Greater discharge at D1 . . . results in GMW that is closer in θ and S to IIW". According to Table 2, it is GMW2 which has properties closer to IIW. Therefore in general this section of the discussion is rather contradictory and needs rethinking. Note that each of the scalings referred to above are the same for a point source plume.

Minor concerns/comments

P4593 line 24 – I don't quite follow why setting the flotation fraction to 1 gives the

maximum catchment area. I don't think this is a general result. If this is a result you have obtained only for this catchment by varying the flotation fraction then perhaps you could insert an additional sentence to clarify this.

P4593 line 28 and other relevant places – Based on Fig 7a, there are only ~3 RACMO 2.3 grid cells in the catchment (though I appreciate that cells outside the catchment will have some effect due to the interpolation). This must presumably reduce confidence in the values of catchment runoff that you use in the plume model. I understand that this is a limitation of the RACMO dataset and therefore there is not much that can be done, but I think the rather large RACMO grid spacing vs catchment size should be acknowledged somewhere, either here or for example in p4598 lines 7-10.

P4595 line 28 – why is it you can assume the bulk of the entrainment was of waters at $\sigma_\theta = 26 - 26.5$ kg/m^3? What about waters with $\sigma_\theta = 25.5 - 26$ kg/m^3?

P4599 line 4 – "depth-integrated" is not appropriate here. It is true that you can integrate the plume equations in Jenkins (2011) to get the solution, but "depth-integrated" here implies some sort of vertical averaging which is not what has been done.

P4600 line 19 – At the prescribed subglacial discharges I believe that submarine melting will have a very small effect on the plume properties (try running the plume model without any submarine melting). If instead we changed the submarine melt parameterization to produce more melting, this would make the plume more buoyant and increase the discrepancy between the plume model depth and the data. Therefore I don't think an incorrect submarine melt parameterization can explain the discrepancy between model and data.

P4600 line 20 – if you use a point source plume then subglacial flux will no longer be a function of channel surface area, removing this possible source of error. But I agree that the subglacial discharge flux could be incorrect. One possible reason for this which I don't think came across in the paper is temporal variability in the subglacial discharge flux over the survey period – either diurnally or from day to day – might this help to explain the rather vertically smeared signal in turbidity you see in Fig 5c?

Technical comments

P4586 line 17 – I think this sentence could be better written to make it clear exactly what is "serving as a mechanism. . ."

P4586 line 20 – I find "higher entrainment" a bit ambiguous. I think it would be better to make a statement to the effect that plumes with larger initial discharges entrain a greater volume of water or set up stronger circulation (Carroll et al., 2015).

P4586 line 28 – suggest rewording to "largely unknown characterization of subglacial discharge" as this then includes hydrology which is brought up in the following sentence.

P4588 line 24 – Am I mistaken that there are in fact three LBL transponders shown in Fig. 3 rather than two as described here? Might this sentence belong better in the previous paragraph (e.g. lines 15-16)?

P4590 line 6 – typo – "and" should be "an"

P4590 line 20 – insert comma after "depth sounder"

P4591 section 3.1 – might this subtitle be changed to something more appropriate? The section appears to discuss fjord bathymetry, subglacial topography, and behaviour of the glacier in recent decades.

P4591 line 26 – I believe this should be Fig. 2b rather than 2a

P4593 line 3 – I believe this should be Table 3 rather than 4.

P4593 line 9 – need a space before "g"

P4595 line 28 – "than" should be "then"

P4598 line 26 – suggest adding "width" to the list of plume properties for completeness.

P4599 line 25 – I think "cross-sectional area" rather than "surface area" is more correct.

P4599 line 29 – I couldn't see where the range in conduit size has come from – does it arise from a range in subglacial discharge?

P4599 line 29 – p4600 line 3 – By using a Röthlisberger channel and the results of Slater et al., 2015, you have already assumed a semi-circular channel so I believe this sentence would belong better at the start of the paragraph which begins in p4599 line 23.

P4600 line 8 – typo – "that" should be "than"

P4601 line 25 – it would be interesting, if you have the data, to know what the discharge through D1 was at this time.

P4602 line 13 – suggest inserting "qualitatively" before "consistent" as you have done in the abstract and conclusion.

P4602 lines 24-26 – don't need two "additions"

P4603 line 26 – it's not GMW1 which enters the fjord, rather it is subglacial discharge from D1 which enters the fjord and subsequently becomes GMW1 after mixing, melting etc. So I suggest changing "GMW1" to "discharge from D1".

P4604 line 8 – typo – need "of" after "couple"

P4604 line 24 – need to correct the spelling of variability

P4604 line 28 – I think one of the original plume papers (e.g. Morton et al 1956) would be a better reference for variability in plume neutral buoyancy.

P4605 line 10 – "amount" should be "amounts"

P4605 lines 14-19 – this sentence doesn't read correctly – does it need "While" at the start?

P4605 line 21 – don't need two citations to the same paper in one sentence.

Table 1 – need to correct spelling of “mission”.

Table 4 – I presume “Plume θ” and “Plume S” refer to values at the neutral buoyancy depth – could this be clarified in the table? Is volume flux used anywhere in the text? If not it might be worth removing.

Figure 1 – the red box in the plot is labelled Fig. 2 – I assume this is meant to be Fig. 3.

Figure 3 – 4th line of caption: “line” should be “lines”

Figure 7 – might the outer fjord CTD markers be a different color than green? They are quite hard to see at present.

Literature cited

Carroll, D., D. A. Sutherland, E. L. Shroyer, J. D. Nash, G. A. Catania, and L. A. Stearns, 2015: Modeling turbulent subglacial meltwater plumes: Implications for fjord-scale buoyancy-driven circulation. Journal of Physical Oceanography, 45 (8), 2169–2185.

Cowton, T., D. Slater, A. Sole, D. Goldberg, and P. Nienow, 2015: Modeling the impact of glacial runoff on fjord circulation and submarine melt rate using a new subgrid-scale parameterization for glacial plumes. Journal of Geophysical Research: Oceans, 120 (2), 796–812.

Jenkins, A., 2011: Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers. Journal of Physical Oceanography, 41 (12), 2279–2294.

Morton, B., G. Taylor, and J. Turner, 1956: Turbulent gravitational convection from maintained and instantaneous sources. Proceedings of the Royal Society of London Series a-Mathematical and Physical Sciences, 234 (1196), 1–23.

Slater, D. A., P. W. Nienow, T. R. Cowton, D. N. Goldberg, and A. J. Sole, 2015: Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. Geophysical Research Letters, 42.

Straneo, F., and C. Cenedese, 2015: The dynamics of Greenland’s glacial fjords and their role in climate. Annual Reviews of Marine Science, (7), 89–112.

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