We highly appreciate helpful comments and suggestions by Reviewer #2. In the following, the comments by Reviewer #2 are underlined and our responses to the comments are in normal characters. Modifications to the text are shown in quotation marks with bold characters indicating newly added text, and normal characters indicating text that was already present in the previous version. The line numbering is referenced to the original copy of the manuscript.

Interactive comment on "Arctic Ocean outflow and glacier–ocean interaction modify water over the Wandel Sea shelf, northeast Greenland" by Igor A. Dmitrenko et al., Anonymous Referee #2

Received and published: 13 August 2017

<u>The authors present a unique dataset of CTD profiles in the Wandel Sea, a previously unsampled region of Northeast Greenland that is subject to a complicated mixture of influences including Arctic ocean outflow (with traces of both Atlantic and Pacific water), ocean-glacier interactions, and irregular ocean-atmosphere interactions (based on the spatially variable history of open water and landfast sea ice).</u>

<u>1. The largely qualitative description of the various observed water masses in terms of sources and physical processes is plausible, however I found that the organization and description of the various clusters, regions, and processes difficult to follow and at times confusing. Additionally, several of the figures are overly complicated and therefore difficult to connect with the conclusions in the text, without a great deal of interpretive effort. To be accepted for publication, I believe that a clearer organization of the results (and figures) would greatly improve the readability.</u>

This comment sounds similar to the general comment on results and figures by Reviewer #1. To improve this, we:

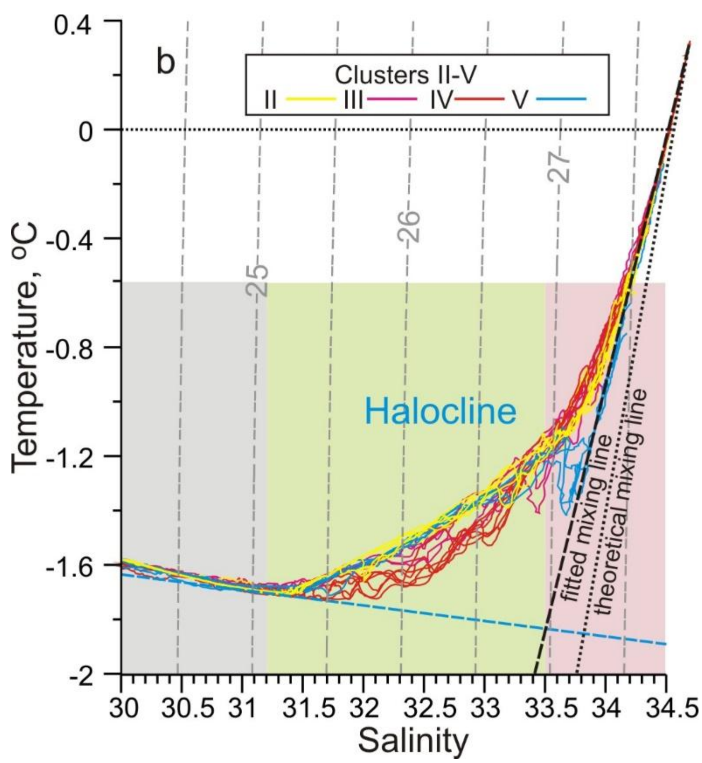
1. Reorganised subchapters in section Results, with new subsection titles that help the orientation as "***3.1. Water mass structure***", "***3.2. CTD clustering***", "***3.2.1. Methods of CTD clustering***" and "***3.2.2. Description of clusters***";
2. Skipped the regions from both description and figures;
3. Removed the terminology that is more commonly used for larger shelves such as outer shelf, mid-shelf and inner shelf;
4. Reduced the description of clusters I and II in subsection 3.2.2 to focus on the key clusters IV and V – lines 204-208 and 216-219 were omitted;
5. Moved the cluster presentation from former Figure 7 upfront to Figure 4b.

The report on figure modifications is provided below.

<u>2. More importantly, I think that the section dealing with the signatures of ocean-glacier interactions needs to be clarified through a more quantitative description of the processes and expected mixing lines and deviations. The calculation of deltaS, along with the vague descriptions of how seawater will cool when it comes into contact with ice are disorganized and not well connected to the current literature of ocean-ice models that are currently in use in many recent manuscripts (e.g. Jenkins, Wilson and Straneo, Mankoff et al 2016, etc). In this treatment, the meltwater mixing line is defined by an end-member corresponding to the "apparent" temperature of a water parcel after losing heat to the ice to overcome the latent heat of melting (and zero salinity). Typically this has a value of approximately -90 degC, and defines a slope against which water properties can be compared to determine e.g. meltwater fractions. No explicit discussion of this approach is made in the manuscript (e.g. by directly applying the</u>

model to the properties observed in the CTD profiles), however some discussion of temperature and salinity changes are made in terms of the transfer of heat and salt into the water column (e.g. lines 310).

We agree with Reviewer #2 that the section dealing with the signatures of ocean-glacier interactions is very descriptive and based on rather qualitative analysis. At the moment, we are working on the CTD data from spring 2016 and 2017 (ambient profiles versus glacier profiles) to further our analysis on the ocean-glacier interaction and to put this in the context of the ocean-ice models. Reviewer #2 referenced to the effective potential temperature T_{eff} defined by Jenkins [1999], and further used for the Greenland glaciers by Straneo et al. [2012], Chauché et al. [2014] etc. The effective potential temperature was reported to be about -90°C [e.g., Jenkins, 1999; Chauché et al., 2014]. This gives the theoretical mixing line between the Atlantic-modified PrW and glacier melt water at zero salinity as defined in figure below by dotted line. In fact, this line is steeper comparing to that obtained from fitting the data for the near-glacier CTD profiles (dashed line in figure below and figures 7 and 7d). We suggest that deflected mixing line for the "glacier" cluster V in Figures 6 and 7d is primarily generated by thermal glacier-ocean interactions, with no significant involvement of the glacier melt water, and thus, cannot be considered as a meltwater line following the suggestions of Jenkins [1998], Straneo et al. [2012], Chauché et al. [2014]. We would like to address this point in our new manuscript based on a more comprehensive data set from 2015-2017.



3. The authors should also clarify how they arrived at the meltwater mixing lines presented in Figures 5 and 6 – is it a result of a derivation of the "virtual temperature" end member, or simply a fit to the observed properties of the near-glacier CTD profiles?

The mixing line shown in Figures 6 and 7d is fitted to the observed properties of the near-glacier CTD profiles. We clarified this in Figure 6 caption as follows: "*An approximation of the meltwater mixing line from interaction with the glacial tongue is derived from Cluster V* ***by fitting the data in TS space****...*".

4. There are also some citation issues, with citations given in the text not matching the bibliography (Jenkins 1998 vs 1999), as well as some citations not present in the bibliography that are cited in the text (Stevens 2015). The bibliography and all citations should be carefully checked for consistency (in addition to the two examples I noted), or managed with a reference manager of some kind.

The citation list was corrected and carefully checked for consistency.

Minor corrections

5. L131: Isn't region 3 located Northeast of Station Nord?

Following comments by Reviewer #1, we removed reference to regions from the text and figures to avoid confusions.

6. L185: No Stevens et al in bibliography

Thank you, the reference to *Stevens et al*., 2016 was added.

7. L189: I think this "new mixing end member" is the thermodynamic "meltwater" end member discussed above? Why is it referred to so cryptically here?

We modified this text in line 189 as follows: "*The displacement of the mixing line suggests **the thermodynamic "meltwater" end member**…*".

8. L225: The use of a "division" symbol is confusing here. Normally it would be a dash, but of course the negative signs would make that even more confusing. Why not use "to"?

Changed as recommended, line 225.

9. L265+: This relates to the qualitative vs quantitative discussion of ocean-ice interaction I discuss above. Do we expect that water should cool to the ambient glacier temperature, or to something reflecting the thermodynamic processes involved (e.g. melting, etc)?

The thermodynamics is definitely involved. The associated thermodynamics is quantitatively discussed in lines 306-335.

10. L276: Jenkins 1999?

Yes, corrected.

11. L280-282: This discussion of the cool/turbid water and the lower boundary of the tongue is confusing and overly qualitative. Is it known that the glacier terminus is floating and not grounded? If so, why would the authors expect that cold/turbid meltwater released from the terminus would be at a neutral density level at the bottom of the glacier? I would expect that typically the salinity reduction due to the meltwater input, followed by turbulent entrainment during buoyant rising would determine a neutral density level somewhere above the depth that the meltwater was released. This is another point that would be clarified by a more rigorous discussion of the ocean-ice interaction processes and models as pointed out previously.

There is no direct evidence that the glacier terminus is floating. The indirect evidences came from

(i) Visual estimates of a glacier elevation above the sea surface;

(ii) Summer oceanographic observations reported by Bendtsen, J., J. Mortensen, K. Lennert, J. K. Ehn, W. Boone, V. Galindo, Y. Hu, I. A. Dmitrenko, S. A. Kirillov, K. K. Kjeldsen, Y. Kristoffersen, D. G. Barber, and S. Rysgaard (2017), Sea ice breakup and marine melt of a retreating tidewater outlet glacier in northeast Greenland (81°N), Sci. Rep., 7, 4941, doi: 10.1038/s41598-017-05089-3;

(iii) Satellite observations on the glacier terminus. During the extraordinary storm in August 2016 few separated icebergs at the glacier front were moved onshore by about 300 m.

We completely agree with Reviewer #2. This is also justified in lines 301-305: "*The density reduction of the ocean water due to added melt water is larger than the density increase due to cooling, and the less saline water will ascend along the lower boundary of the glacier, until it reaches the vertical terminus. At this point the water will penetrate into the ambient water column at its density level, forming colder, less saline isopycnal intrusions*". The point is that during winter the subglacial runoff is likely negligible, and the salinity redaction is partly compensated by temperature reduction. So, the density redaction is insignificant, and the neutral density level is not much shallower than the bottom of the glacier as follows from Figure 8. The equilibrium depth for the water parcel affected by glacier melt (salinity redaction about 0.2) is about 2-3 m shallower comparing with water parcel not affected by glacier melt.

<u>12. L304: Related – where exactly *is* the neutral density level for this water?</u>

We modified this sentence in lines 303-305 as follows: "*At this point the water will penetrate into the ambient water column at its density level* ***few meters above the depth that the meltwater was released****, forming colder, less saline isopycnal intrusions*".

<u>13. L309: the deltaS equation – what is the source/citation for this? How is it derived?</u>

This is the balance equation. If certain amount of heat is consumed for melting (resulting in cooling by ΔT) then salinity is reduced by ΔS. We slightly modified this equation for simplicity: $\Delta S = S / (L/C_p \Delta T - 1)$

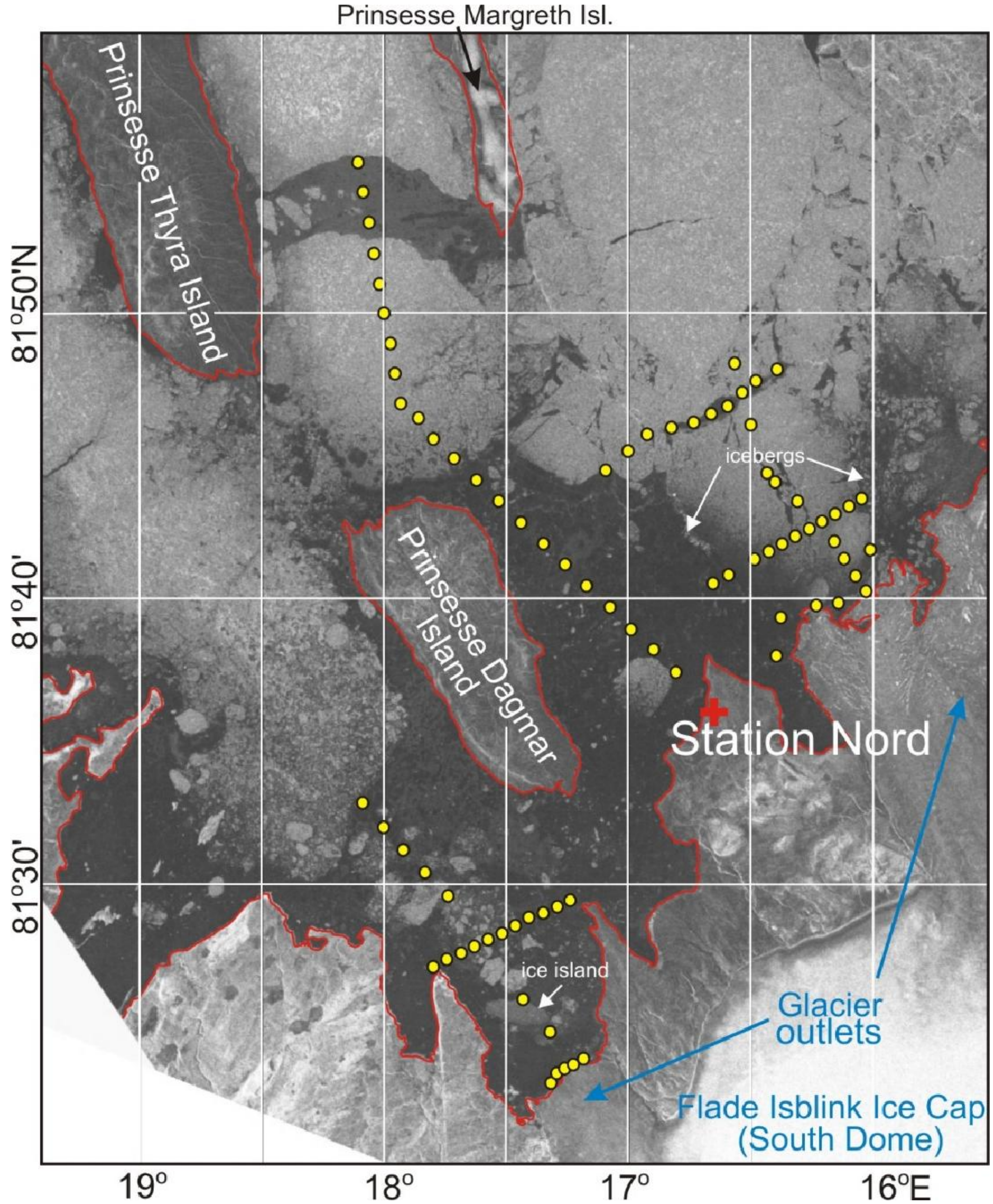
<u>## Figures</u>

<u>14. Figure 2 - L800: "rectangle"</u>

Fixed.

<u>15. Figure 3: This figure contains many aspects that are nearly impossible to read, including: the red overlying text, the color scale for station depths, and the white/black circles. It appears that some points are larger than others, which is not discussed in the caption (and may just be a visual trick owing to the white/black borders).</u>

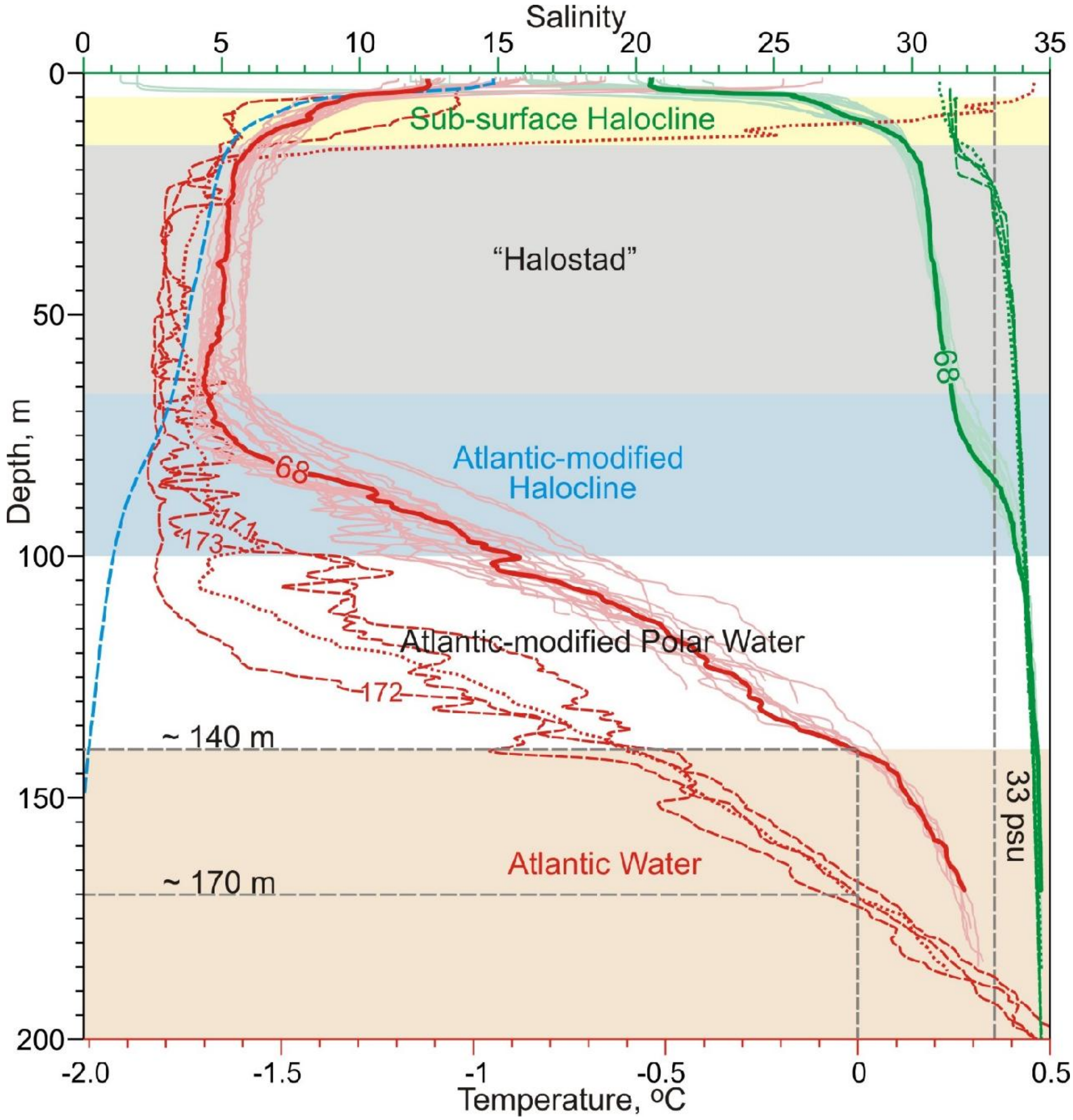
This figure was divided to Figure 3 (satellite imagery and satiation map without station numbers) and Figure 4a (bottom topography). The station numbers for stations >100 m depth were moved to new Figure 4b.



New Figure 3

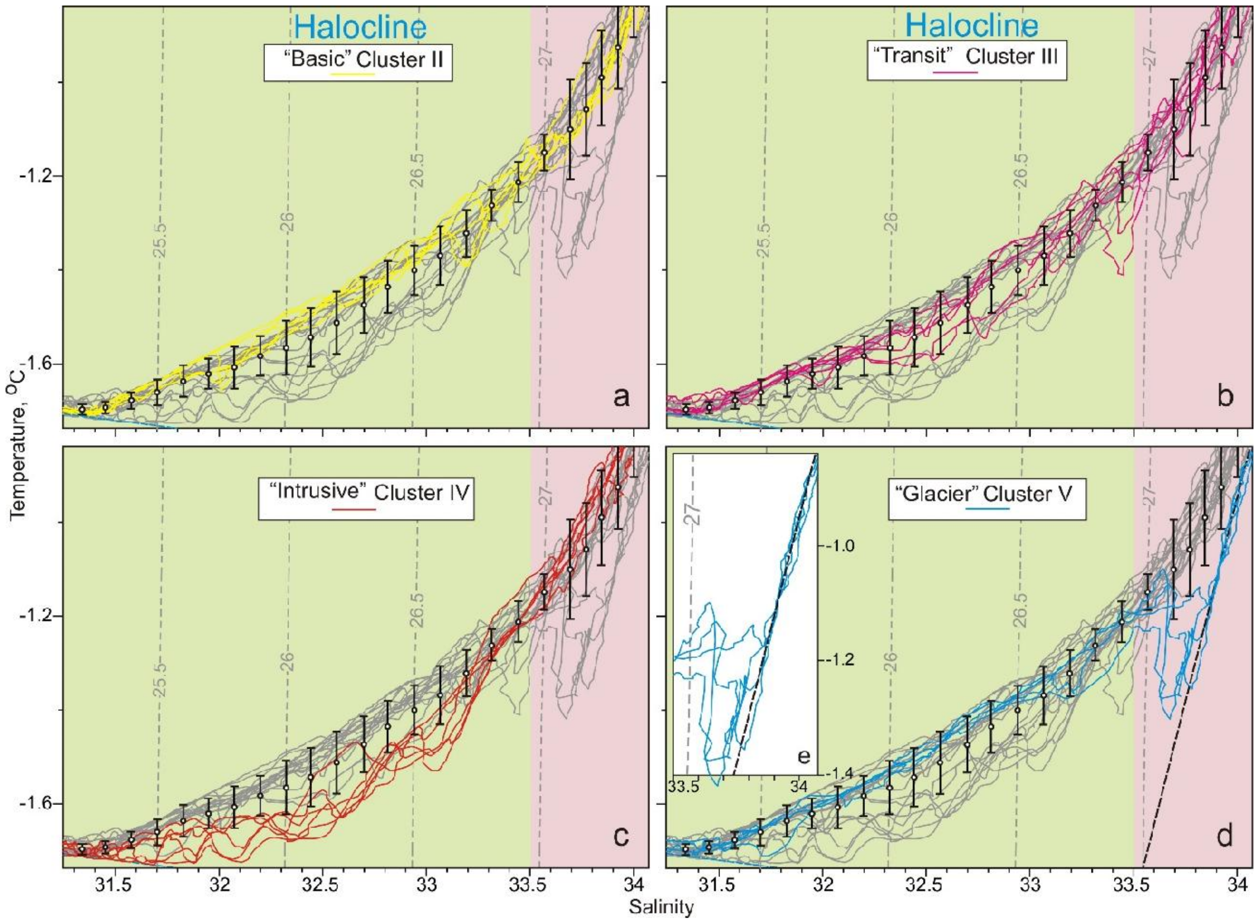
16. Figure 4: In general, I find the profile (and TS) figures with many profiles overlain with different colors, line styles, and x-axes very difficult to interpret (see main review). I recommend either separating out the different plot types, or perhaps making subplots for the different groups of profiles that overlay the group of interest over the other lines which are colored in grey (so that the relative differences can be seen, but without the visual confusion).

To simplify Figure 4, we shaded the whole bundle of profiles and highlighted only the typical profile for station #68 from the “basic” cluster II.



New Figure 4

We also modified Figure 5b to differentiate clusters II-V only by colors. In general, Figure 5b is intended to provide only the general overview on clusters over the extended temperature and salinity range. In contrast, Figure 7 gives more detailed view for the halocline layer. Following this comment, we divided Figure 7 to four different panels showing TS curves for each cluster separately as was recommended by Reviewer #2.



New Figure 7

<u>17. Figure 5 - L830: Should the reference be to Figure 6a?</u>

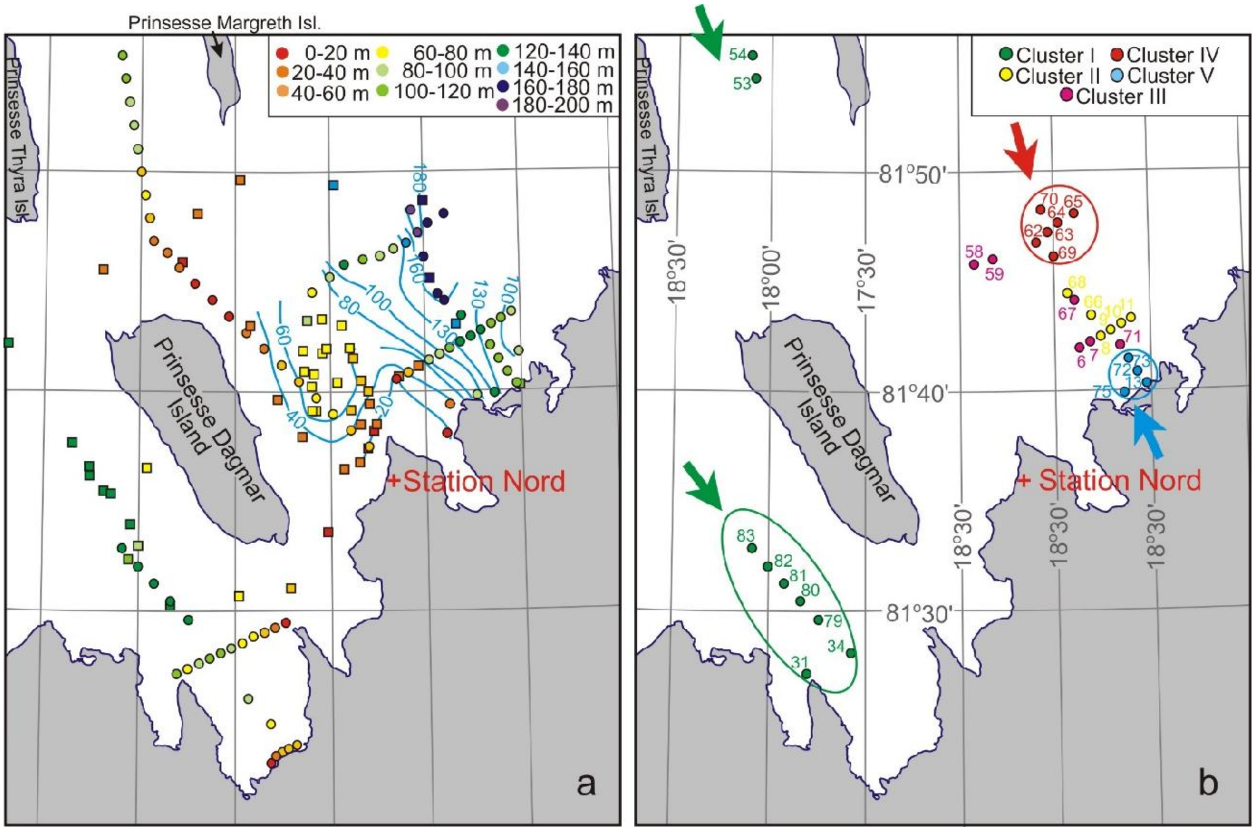
Yes, now it is referenced to Figure 7. Fixed.

<u>18. Figure 5 - L835: Is the meltwater mixing line "derived" from the theory/model, or simply from fitting the data in TS space?</u>

This line was derived by fitting the data in TS space. We modified this sentence in Figure 6 caption as follows: "*An approximation of the meltwater mixing line from interaction with the glacial tongue is derived from Cluster V* ***by fitting the data in TS space*** *(thick black dashed line)*.".

<u>19. Figure 7: The colors of clusters III and IV are indistinguishable.</u>

Figure 7 was moved upfront to Figure 4b. In our copy, the cluster III (purple) is well distinguished from cluster IV (red) – see figure below.



New Figure 4

20. Figure 8: Like Figure 4, the combination of colors, line types, and x-axes makes this plot difficult to interpret. Again, I recommend trying to separate out into subplots.

We simplified Figure 8 by removing the 21 April CDOM profile as recommended by Reviewer #1.