We highly appreciate helpful comments and suggestions by both reviewers. In the following, the comments by reviewers 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 marked-up manuscript version.

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 #1

Received and published: 3 July 2017

Review of Dmitrenko et al. "Arctic Ocean outflow and glacier-ocean interaction modify water over the Wandel Sea shelf, northeast Greenland"

<u>**Summary:** the paper investigates water masses and water column structures based on CTD profiles collected in 2015, and aims at identifying relevant processes and interactions between the different local and advected water masses. The study region is very remote, and largely unexplored, and the spring sampling campaign resulted in a quite unique dataset. While the main conclusions of this paper appear plausible, I find that text and figures need to be improved to convincingly present the main points. In the current form, the text is not easy to follow and could be significantly improved, in particular the introduction and parts of the results and discussion. Some of the figures are very busy, and require a tedious amount of time to identify the relevant details as mentioned in the text. Overall, I find that the paper presents very interesting data and summarizes four plausible main findings at the end of the paper, but requires some major improvements in text and figures to convincingly guide the reader through the paper.</u>

<u>Below please find some general comments as well as more specific recommendations.</u>

<u>**1. Introduction:** I suggest that the introduction should better introduce the study region and better highlight the significance of the presented scientific aspects. I imagine that most readers are not familiar with the Wandel Sea, and more details may be needed to provide the background necessary to understand the region's relevance as is discussed in the text. Parameters such as area/width of the shelf, depth, bathymetry... How does this shelf compare with other Arctic shelves or is the Wandel Sea rather a glacial inlet or so rather than a shelf? From the maps provided in the paper, I don't get a sufficient idea of the relevance of this region beyond the local scale. However, since the aim is clearly to connect the region with upstream and downstream conditions as well, a more comprehensive introduction might help. A stronger formulation of scientific objectives is needed, rather than to "...investigate the vertical CTD profiles..." (lines 66-67).</u>

The introduction was substantially edited to address questions pointed out by Reviewer #1. The following text was introduced:

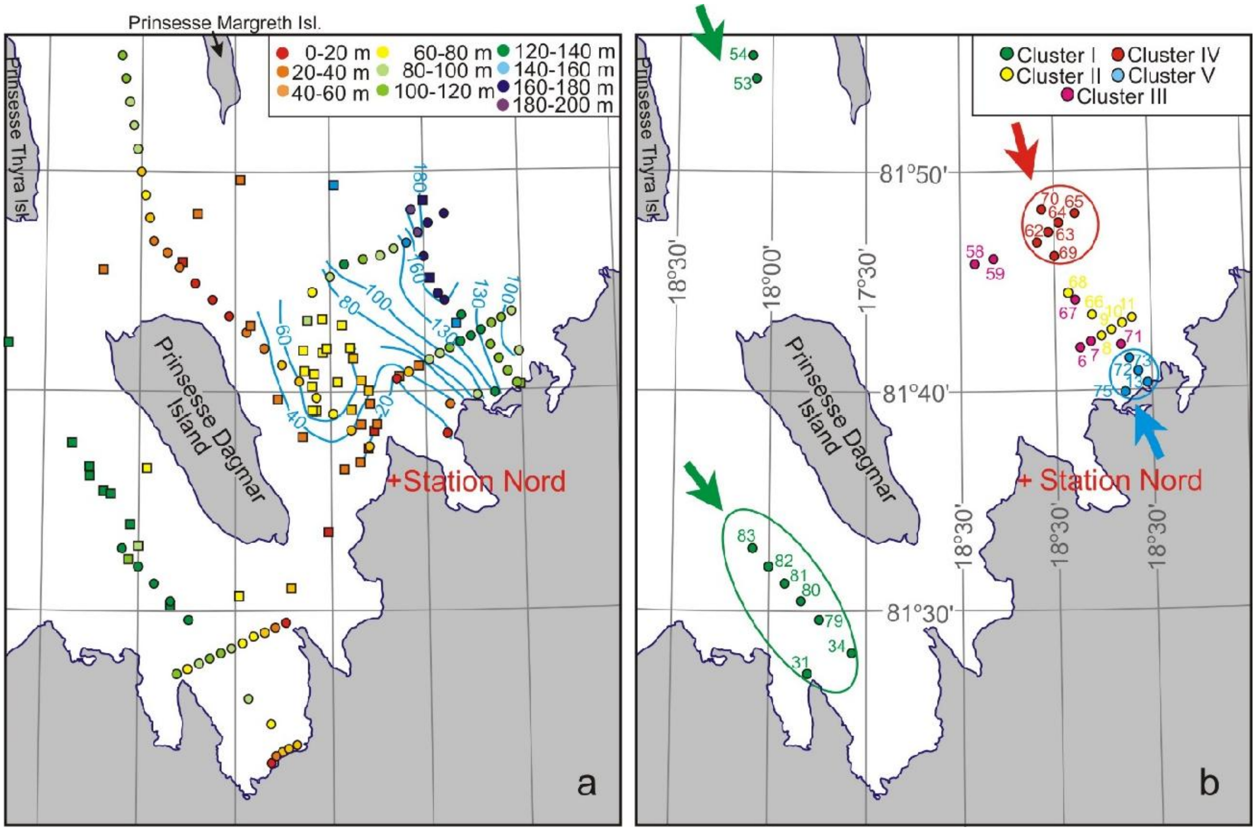
1. Lines 53-54: "***The Wandel Sea is predominantly covered by landfast multiyear sea ice all year around, and only the interior of fjords may become ice free during late summer (Figure 2b)***."
2. Lines 57-60: "***In general, the Wandel Sea is rather a glacial inlet than a shelf sea. It is comprised by several fjords open to the continental slope (Figure 2b). The landfast ice edge in Figure 2b roughly marks the Wandel Sea continental shelf break located in about 35-45 km from the fjord mouths. The bathymetry of the Wandel Sea shelf and upper continental slope is poorly known***."

3. Lines 72-76: "**The coastal branch of the Pacific water flow along the southeast coast of Greenland was reported based on observations** [***e.g., Bacon et al., 2002; Sutherland and Pickart, 2008; Sutherland et al. 2009] and numerical simulations [Hu and Myers, 2013; Aksenov et al., 2016]. However, the pathways of the low salinity Pacific water along the northeast coast of Greenland are debatable***.".
4. Lines 81-87: "***The interaction of warm Atlantic Water with tidewater glacier outlets along the southeast coast of Greenland results in ocean-driven glacier melting. This generates additional fresh water flux contributing to the regional fresh water budget [e.g., Straneo et al., 20011, 2012; Sutherland and Straneo, 2012; Inall et al., 2014]. For the Wandel Sea shelf, the efficiency of the glacier-ocean interaction is not assessed because of the unknown oceanographic conditions at the glacier-ocean interface***.".
5. Sentence in lines 88-91 was modified as follows: "*This paper is focused on analysis of the first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf collected from the landfast ice in April-May 2015* ***(Figure 3) to put this region in the context of upstream, downstream and local conditions with a special focus on the Arctic Ocean outflow and ocean-glacier interaction***.".
6. Sentence in lines 93-95 was updated as follows: "*Our objectives were to investigate the principal features of vertical profiles of salinity and temperature taken over the shelf regions deeper than 100 m* ***for tracing the water origin and local modifications***.".

2. Results: the results are difficult to follow. In particular the clustering is somewhat confusing and not obvious why this is done. Perhaps a better organization into subchapters might help, with section titles that help the orientation. The introductory sentence for the clustering is given in lines 197-199, but may be better before the clusters are introduced. Are all 5 clusters needed for the paper or could the paper do with less for a better overview? There are 5 clusters and 3 regions defined and I wonder if this is necessary. From the map I cannot distinguish between an outer shelf and a mid-shelf region (regions 1 and 2), but perhaps I am just confused by the terminology that is more commonly used for larger shelves. What is the connection between the two regions that are summarized in cluster 1? Perhaps Figure 7 might be better placed at the beginning of the cluster presentation rather than at the end.

Responding this comment by Reviewer #1, we:

1. Reorganised subchapters, 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. Removed reference to regions from both text 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 243-248 and 255-258 were omitted;
5. Moved upfront to Figure 4b the cluster presentation in Figure 7.



New Figure 4

The two regions summarized in cluster I were ice-free during the preceding summers that results in a relatively warm Halostad for the open water cluster I. This explanation is provided in cluster description in lines 248-251. Only three clusters (II, IV and V) are discussed in this manuscript, but for the comprehensive analysis all profiles >100 m depth were processed, clustered and described. Regions were completely omitted.

3. Ocean glacier interaction subchapter: Would an estimate of glacial melt due to glacier-warm water interaction be not as interesting as calculating salinity differences considering the high interest in Ocean-glacier interaction?

Yes, it would. However, we have no information on the time scale of the ocean-glacier interaction. Without time dimension, we cannot estimate heat fluxes and associated melt rate.

4. L389: Upwelling over the continental slope: Seems random. What kind of upwelling, was upwelling documented before, and where is the Wandel Sea continental slope with respect to your study region?

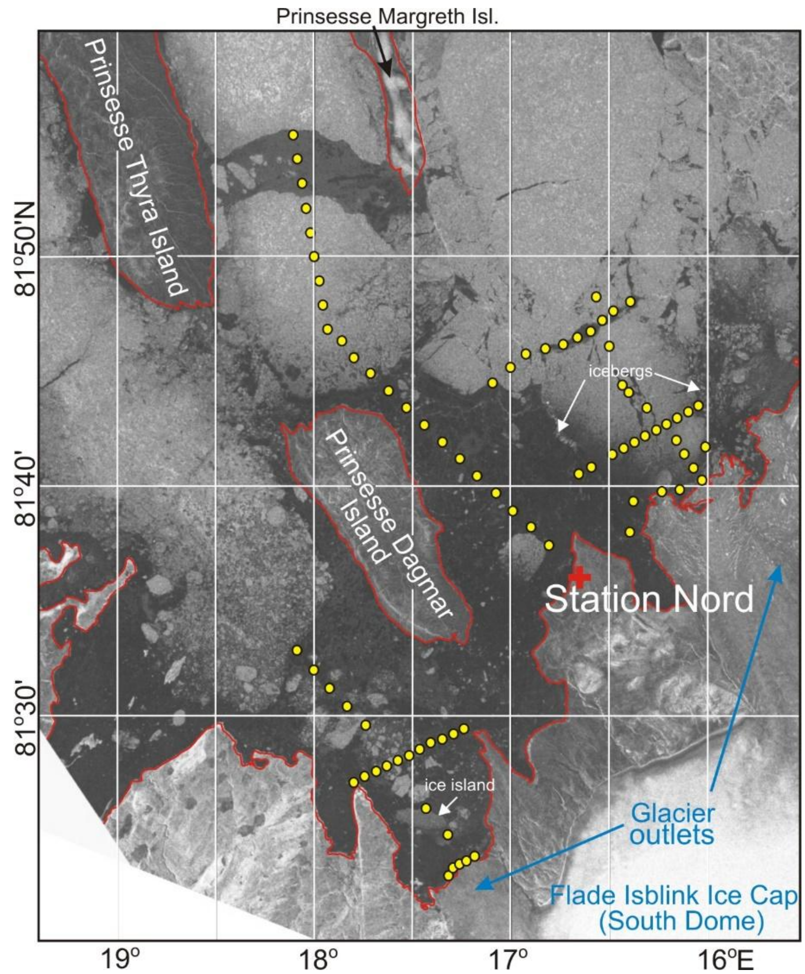
The upwelling was hypothetically suggested to explain the difference between the on-shelf and off-shelf water mass structure. This is pointed out in lines 439-440: “*Hypothetically, the wind-driven upwelling of the Atlantic-modified PrW and AW over the continental slope can result in uplift of the water masses over the outer shelf.*”. There are no instrumental observations of upwelling in this area. We specify position of the continental slope in lines 58-59 as follows: “***The landfast ice edge in Figure 2b roughly marks the Wandel Sea continental shelf break located in about 35-45 km from the fjord mouths***.”.

Figures:

5. Map: A map showing topography and stations on a regional scale might help to put the region into a better context. Figure 1 is good to have for the large-scale circulation, Figure 2 shows where glacier and polynyas are located, Fig.3 shows the ice conditions during the survey, but the reader has no idea what the greater region looks

like, i.e. where is the continental slope that is mentioned in the text. Shelf-slope interaction is one focus of the paper, but not clear to me where this takes place.

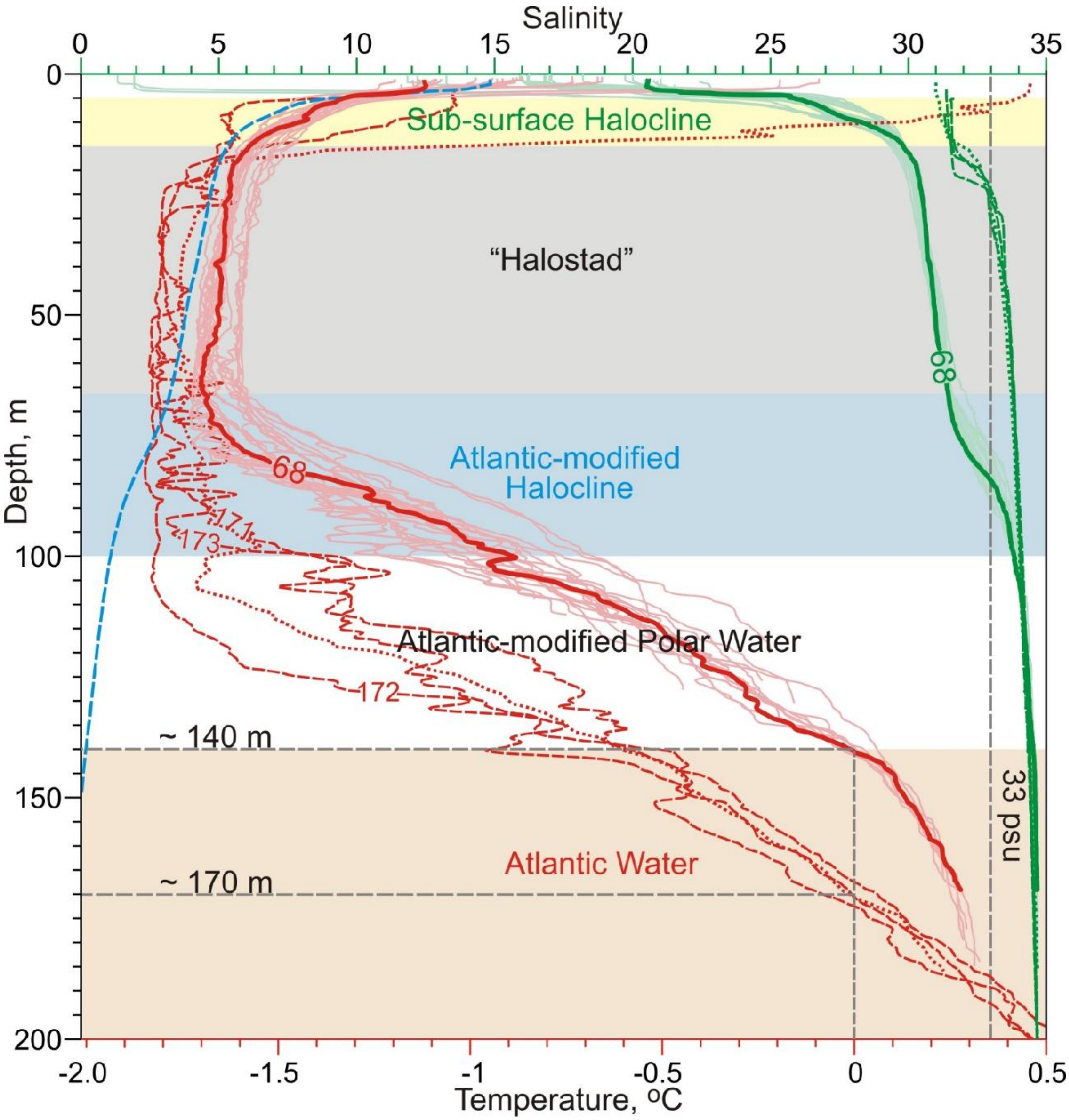
We specified position of the continental slope in introduction, lines 58-59 as follows: "***The landfast ice edge in Figure 2b roughly marks the Wandel Sea continental shelf break located in about 35-45 km from the fjord mouths***.". Figure 3 was modified to focus on ice conditions. The bottom topography was moved to new Figure 4a, and Figure 4b shows stations >100 m depth and CTD clusters.



New Figure 3

6. Fig4: In my opinion this figure is too busy. There are too many lines in there with colors that are not immediately distinguishable. I would strongly suggest to try to make this more user-friendly. Perhaps only show mean profiles rather than the whole bundle, or remove those profiles that are not absolutely necessary. Understanding this figure requires multiple readings of the captions which distracts from the text. Same problem with some of the other figures.

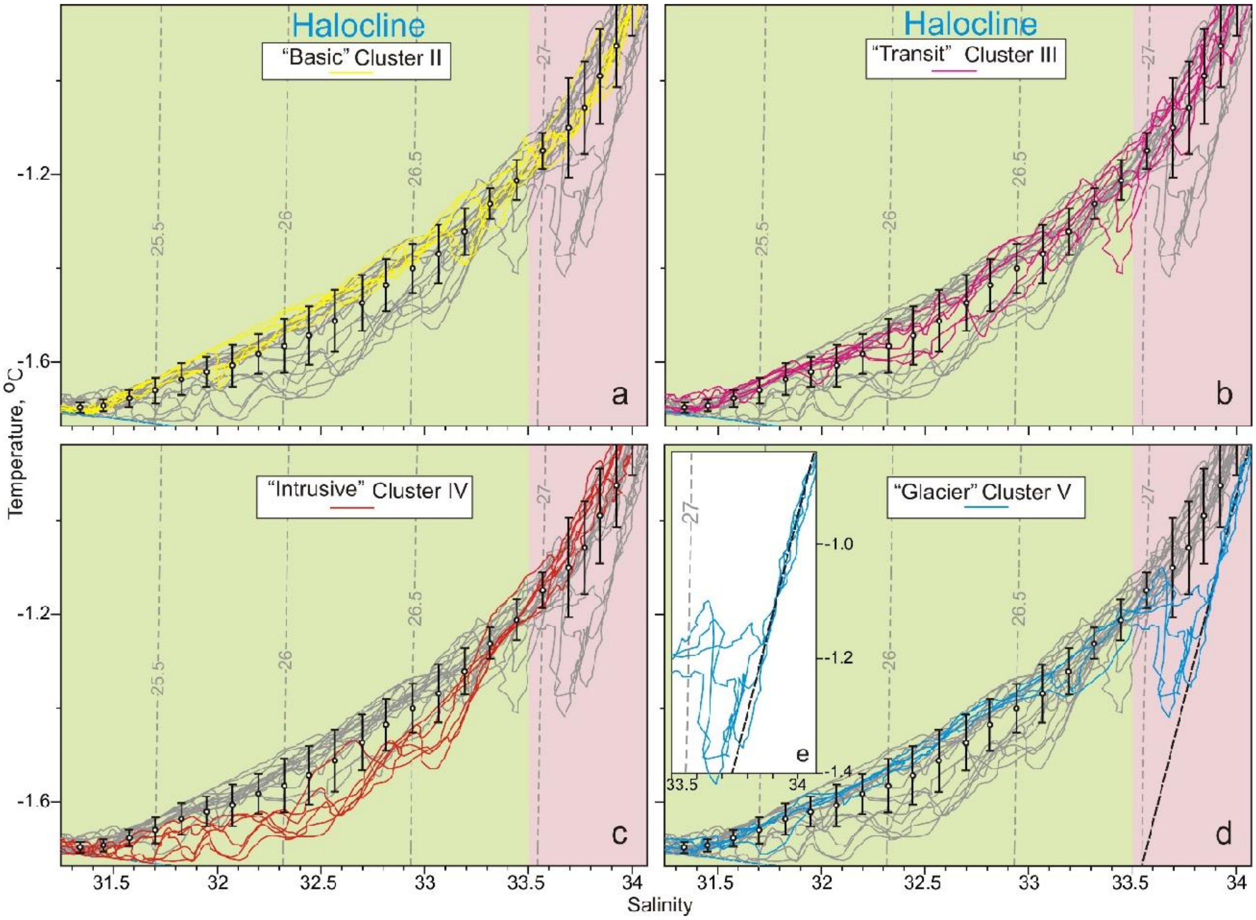
To simplify this new Figure 5, we shaded the whole bundle of profiles and highlighted only the typical profile for station #68 from the "basic" cluster II.



New Figure 5

7. Fig5: Somehow the different dashed lines are confusing and by the time I read through the caption to identify what the different lines indicate I forgot what the figure is supposed to tell us. Could this be made more user-friendly? Also, the box refers to Fig6, not Fig 5.

We modified Figure 5b (new Figure 6b) to differentiate clusters II-V only by colors. In general, Figure 6b is intended to provide only the general overview on clusters over the extended temperature and salinity range. In contrast, new Figure 7 gives more detailed view for the halocline layer. Moreover, we divided Figure 7 to four different panels showing TS curves for each cluster separately as was recommended by Reviewer #2. The figure reference number for the box in Figure 6b was fixed.



New Figure 7

<u>8. Fig7: How are the clusters related to regions? That part seems confusing. Is there a continental slope that can be displayed in this figure to show where potential interaction with ambient waters could take place?</u>

We removed reference to regions from the text and figures to avoid confusions. Figure 7 was moved upfront as recommended and comprised the new Figure 4b (see above). The continental slope is out of the Figure 4b spatial scale. However, we specify position of the continental slope in lines 58-59 as follows: "***The landfast ice edge in Figure 2b roughly marks the Wandel Sea continental shelf break located in about 35-45 km from the fjord mouths***.".

<u>9. Fig8: I would suggest to reduce the information displayed to a minimum. A paper that requires a detailed study of each figure caption in order to understand the figures quickly becomes unattractive for the readers. Perhaps show either the mean or just the 21 April profile. Details or differences between the two are not discussed in the text anyway...</u>

We removed the 21 April CDOM profile from Figure 8.

<u>Minor comments:</u>

<u>10. L89-92: Locations are not shown in a map, therefore it is not clear where these stations are and why they are used</u>

We roughly identify this location in Figure 1. The figure caption was modified accordingly adding the following text (lines 760-761): "***The blue dot roughly identifies location where CTD profiles were collected in the Beaufort Sea***. ".

<u>11. L91: “meridian” is not needed</u>

Modified as requested in line 119.

<u>12. L136-138: were those the “normal” ice conditions?</u>

We modified this text in lines 161-164 as follows: “*During the field campaign this region was covered with a mix of first year (~1.2 m thick) and multiyear sea ice (~3 m thick), with icebergs and an ice island frozen within the fast ice (Figure 3)* ***that corresponds to the typical ice conditions over this area*****.”.**

<u>13. L141: as a result of ice melt and glacier runoff. Can you provide more details at least qualitatively which of the two is more important?</u>

To clarify this point we make reference to Bendtsen et al. [2017], lines 596-599: ***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.***

<u>14. L167: dotted line is very difficult to see</u>

We make the dotted lines thicker in Figure 4 (see new Figure 5 above).

<u>15. L171: this sentence kind of downgrades your analysis, perhaps mention why it is still worthwhile to do here...</u>

We modified this sentence in lines 200-202 as follows: “*We note, however, that the synoptic, seasonal and interannual variability can be significant [e.g., Falck et al., 2005] making it difficult to interpret the snapshot data from the Wandel Sea continental slope****, while this analysis appears important and plausible***.”.

<u>16. L175: ...were subdivided into clusters... Why? I think an explanation is needed here on why the data are subdivided and what one is hoping to learn from this</u>

We introduced new sentence in lines 209-210 as follows: “***The clustering was conducted to assess the origin of water masses, and to identify the shelf-slope and ocean-glacier interactions***.”.

<u>17. L283: “water dynamics”... I would just say “currents are too weak”</u>

Changed as requested, line 323.

<u>18. L289: insignificant sub glacier freshwater discharge. Is it really insignificant? It sounds more important when you talk about it earlier...</u>

We have no evidence of surface freshening along the glacier termination during winter (e.g., Figure 8).

<u>19. L298: heat conduction into the glacier: are there more details regarding this subject, or papers that deal with this? Seems a bit random there...</u>

We have no information on the vertical temperature profile in the glacier. So, any assumptions on the rate of the heat conduction into the glacier are very speculative.

<u>20. L337: 4.2 interaction with ambient water from the continental slope... interaction of what? Incomplete title...</u>

We modified this title (line 375) to: “***Shelf water*** *interaction with ambient water from the continental slope*”.

<u>21. L404: is pers. communication from a co-author the correct referencing?</u>

This reference in lines 436-437 was changed to "***Kirillov, S., I. Dmitrenko, S. Rysgaard, D. Babb, L. T. Pedersen, J. Ehn, J. Bendtsen, and D. Barber (2017), Storm-induced water dynamics and thermohaline structure at the tidewater Flade Isblink Glacier outlet to the Wandel Sea (NE Greenland), Ocean Sci. Discuss., doi: 10.5194/os-2017-60.***"**.**

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

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).

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.

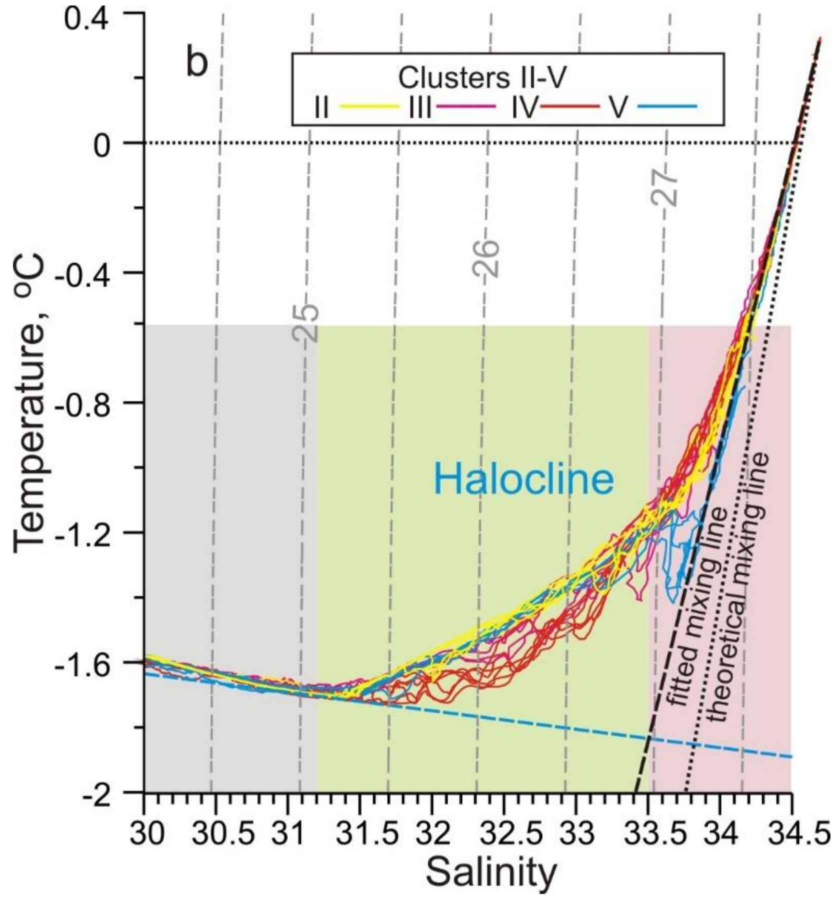
This comment sounds similar to the general comment on results and figures by Reviewer #1. To improve this, we:

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 243-248 and 255-258 were omitted;
5. Moved the cluster presentation from former Figure 7 upfront to Figure 4b.

The report on figure modifications is provided below.

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 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.



<u>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?</u>

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 (lines 816-817) 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 (lines 583-584, 702-706, 713-717, 723-725, 735-737).

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, lines 713-717).

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 lines 222-223 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 265.

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 333-373.

10. L276: Jenkins 1999?

Yes, corrected in line 315.

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.

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

We modified this sentence in lines 342-344 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*".

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

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, line 348: $\Delta S = S / (L/C_p \Delta T - 1)$

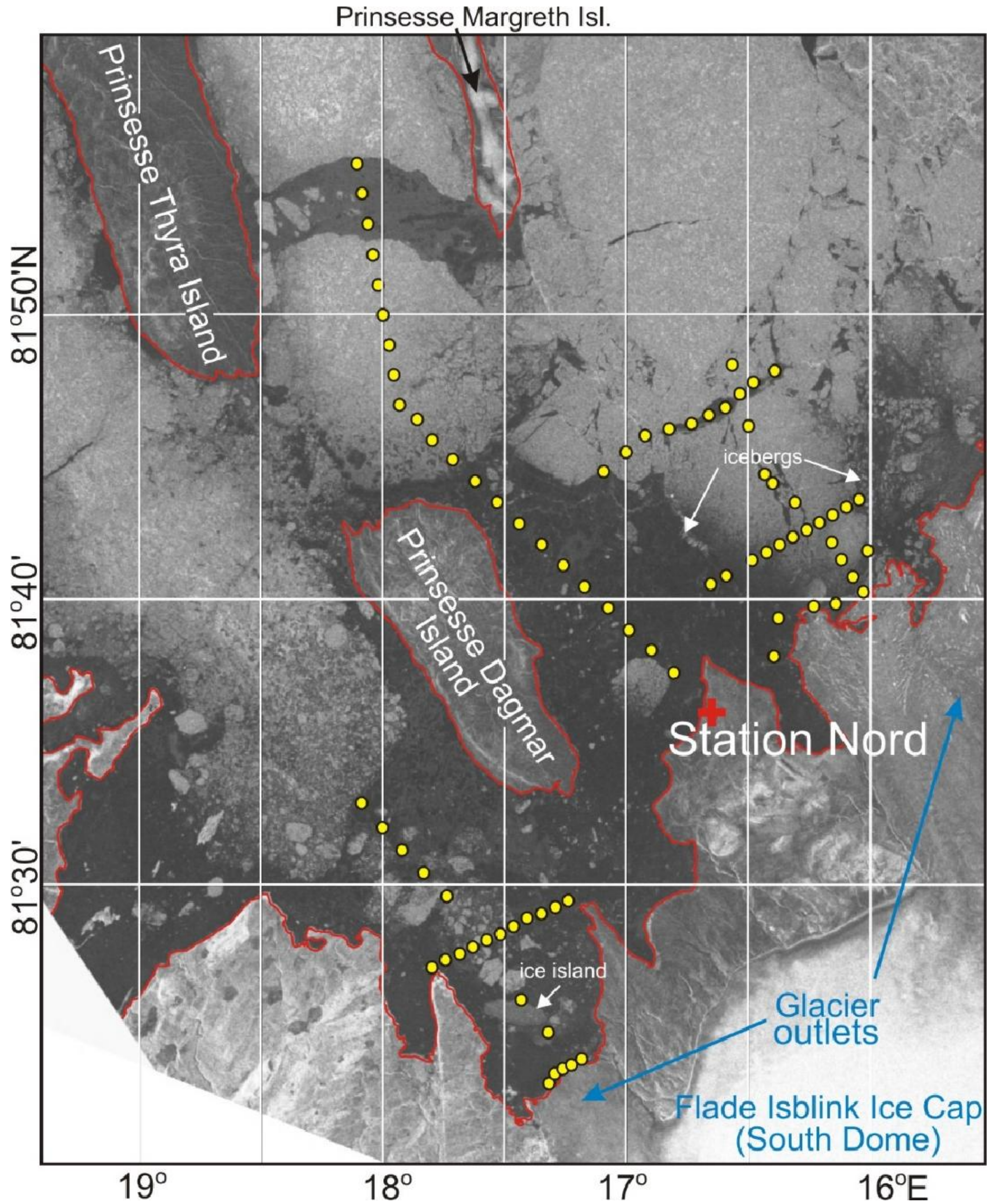
Figures

14. Figure 2 - L800: "rectangle"

Fixed in line 771.

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).

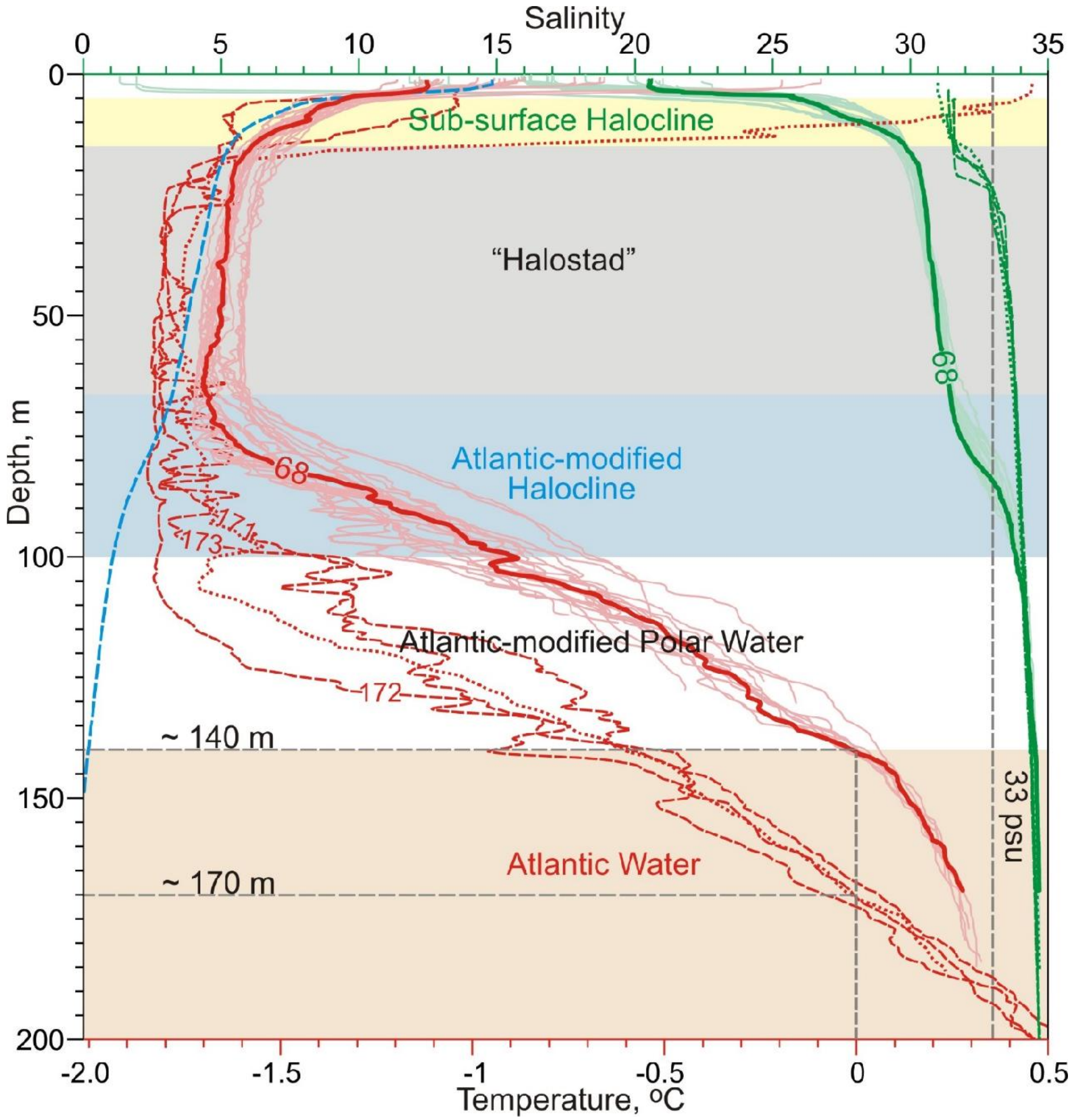
This figure was divided to Figure 3 (satellite imagery and satiation map without station numbers) and Figure 4a (bottom topography). The station numbers for stations >100 m depth were moved to new Figure 4b.



New Figure 3

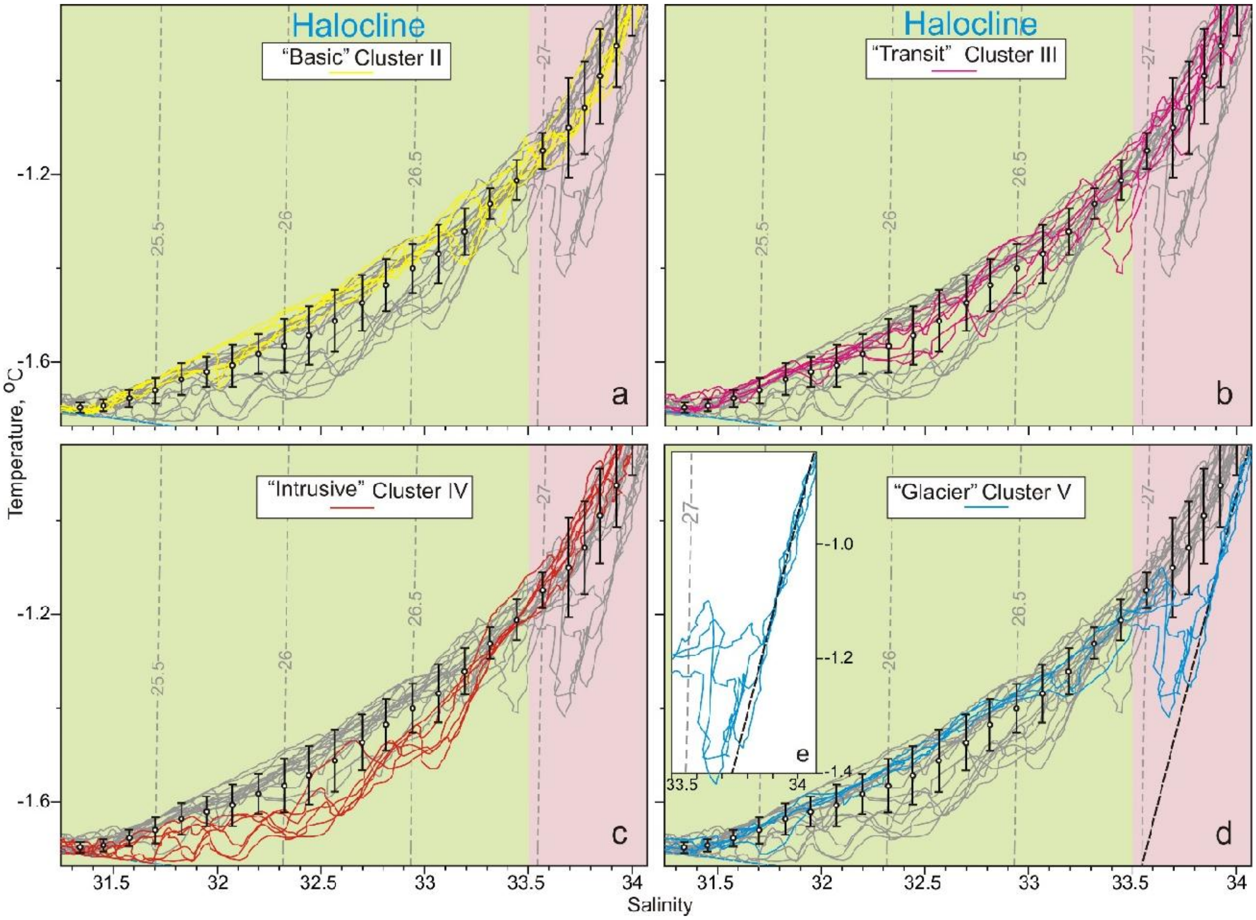
<u>16. Figure 4: In general, I find the profile (and TS) figures with many profiles overlain with different colors, line styles, and x-axes very difficult to interpret (see main review). I recommend either separating out the different plot types, or perhaps making subplots for the different groups of 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).</u>

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>

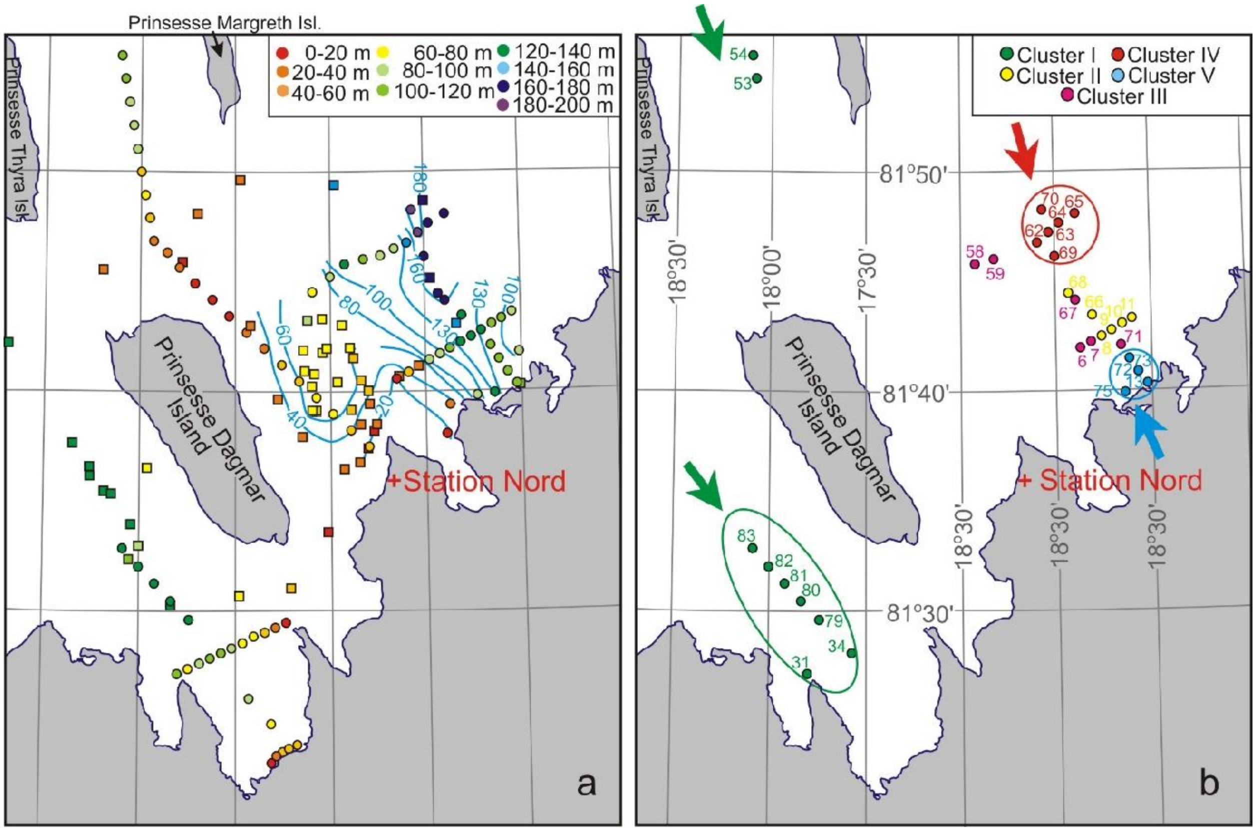
Yes, now it is referenced to Figure 7. Fixed.

<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 (lines 816-817) 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

<u>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.</u>

We simplified Figure 8 by removing the 21 April.

Arctic Ocean outflow and glacier-ocean interaction modify water over the Wandel Sea shelf (Northeast Greenland)

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Abstract: The first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf in North Eastern Greenland were collected in April-May 2015. They were complemented by CTDs taken along the continental slope during the Norwegian FRAM 2014-15 drift. The CTD profiles are used to reveal the origin of water masses and interactions with ambient water from the continental slope and the tidewater glacier outlet. The subsurface water is associated with the Pacific Water outflow from the Arctic Ocean. The underlying Halocline separates the Pacific Water from a deeper layer of Polar Water that has interacted with the warm Atlantic water outflow through Fram Strait recorded below 140 m. Over the outer shelf, the Halocline shows numerous cold density-compensated intrusions indicating lateral interaction with an ambient Polar Water mass across the continental slope. At the front of the tidewater glacier outlet, colder and turbid water intrusions were observed at the base of the Halocline. On the temperature-salinity plots these stations indicate a mixing line that is different from the ambient water and seems to be conditioned by the ocean-glacier interaction. Our observations of Pacific Water are set within the context of upstream observations in the Beaufort Sea and downstream observations from the Northeast Water Polynya, and clearly show the modification of Pacific water during its advection across the Arctic Ocean. Moreover, ambient water over the Wandel Sea slope shows different thermohaline structures indicating the different origin and pathways of the on-shore and off-shore branches of the Arctic Ocean outflow through western Fram Strait.

1. Introduction

One of the most significant global issues over the last decade has been the vast change in the Arctic region. The Arctic Science Partnership (ASP) consortium (www.asp-net.org) was established to understand connections and processes linking climate, cryosphere, ocean and ecosystems. Under the framework of ASP, an extensive oceanographic field campaign took place during April and May 2015 from the landfast sea ice that covers the shelf of the Wandel Sea.

The field campaign was based out of the new Villum Research Station located at the Danish military outpost Station Nord at 81°36N, 16°40W on Prinsesse Ingeborg Peninsula in the very north-eastern corner of Greenland (Figures 1 and 2). Northern Greenland is among the most remote wildernesses of the northern hemisphere. Station Nord features a very cold polar tundra climate with an average temperature during winter below -30°C and just a few degrees above the freezing point in the midst of the short summer.

The Wandel Sea is predominantly covered by landfast multiyear sea ice all year around, and only the interior of fjords may become ice free during late summer (Figure 2b). The Flade Isblink Ice Cap is located close to Station Nord (Figures 2b and 3). It is an isolated ice cap with a surface area of 5 000 km^2 and maximum thickness of 600 m that overlies bedrock that is on average 100 m below sea level [e.g., *Palmer et al*., 2010; *Rinne et al*., 2011]. In general, the Wandel Sea is rather a glacial inlet than a shelf sea. It is comprised by several fjords open to the continental slope (Figure 2b). The landfast ice edge in Figure 2b roughly marks the Wandel Sea continental shelf break located in about 35-45 km from the fjord mouths. The bathymetry of the Wandel Sea shelf and upper continental slope is poorly known.

~~Prior to our field program in 2015, there were no oceanographic or *in situ* sea ice observations over the Wandel Sea shelf.~~ *Nørgaard-Pedersen et al*. [2008] provided limited information on the bottom topography in the area surrounding Station Nord, specifically the existence of several submarine glacial troughs, with depths of up to ~180 m, that open to the continental slope (Figure 4a~~3~~). The bathymetry of the Independence and Denmark fjords is unknown.

Prior to our field program in 2015, there were no oceanographic or in situ sea ice observations over the Wandel Sea shelf. From very general considerations, the Wandel Sea shelf is expected to be under the influence of the Arctic Ocean outflow through western Fram Strait (Figure 1). The upper layer (down to 400 m) of this outflow is comprised of low salinity surface Polar Water partly including low salinity water of Pacific origin, and the intermediate water (> 150-200 m) of Atlantic origin [e.g., *Rudels et al*., 2002; 2005]. The freshwater export through western Fram Strait is an important component of the Arctic Ocean freshwater budget that links the Arctic Ocean to the global climate system [e.g., *de Steur et al*., 2009]. The coastal branch of the Pacific water flow along the southeast coast of Greenland was reported based on observations [e.g., *Bacon et al*., 2002; *Sutherland and Pickart*, 2008; *Sutherland et al*. 2009] and numerical simulations [*Hu and Myers*, 2013; *Aksenov et al*., 2016]. However, the pathways of the low salinity Pacific water along the northeast coast of Greenland are debatable. The Wandel Sea shelf can also be a source of freshwater that originates from summer snow/sea ice meltwater and from glacier-derived freshwater.

The Atlantic Water outflow through Western Fram Strait with temperatures above 0°C in the intermediate water layer (> 150-200 m) closes the circulation loop of the Atlantic Water in the Arctic Ocean conditioned by its inflow through eastern Fram Strait and Barents Sea [e.g., *Rudels et al., 1994*; *Rudels*, 2012] – Figure 1. The interaction of warm Atlantic Water with tidewater glacier outlets along the southeast coast of Greenland results in ocean-driven glacier melting. This generates additional fresh water flux contributing to the regional fresh water budget [e.g., *Straneo et al*., 2011, 2012; *Sutherland and Straneo*, 2012; *Inall et al*., 2014]~~The Wandel Sea shelf can also be a source of freshwater that originates from summer snow/sea ice meltwater and from glacier-derived freshwater.~~ For the Wandel Sea shelf, the efficiency of the glacier-ocean interaction is not assessed because of the unknown oceanographic conditions at the glacier-ocean interface.

This paper is focused on analysis of the first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf collected from the landfast ice in April-May 2015 (Figure 3) to put this region in the context of upstream, downstream and local conditions with a special focus on the Arctic Ocean outflow and ocean-glacier interaction~~.~~ This data set ~~They were~~was complemented by CTDs taken in June-July 2015 over the Wandel Sea continental slope during the Norwegian FRAM 2014-15 sea ice drift (Figure 2b). Our objectives were to investigate the principal features of vertical profiles of salinity and temperature taken over the shelf regions deeper than 100 m for tracing the water origin and local modifications.

The paper is structured as follows. Section 2 describes observational data on CTD, sea-ice and bottom topography, and justifies the selection of CTD data for our analysis. Section 3 provides detailed description of the water mass structure over the Wandel Sea shelf and continental slope, methods of clustering the CTD profiles and the CTD clusters. Section 4.1 discusses oceanographic patterns of the "glacier" CTD cluster with respect to the ocean-glacier interaction. Section 4.2 focuses on the "intrusive" CTD cluster from the Wandel Sea outer shelf. Sections 4.3/4.4 discuss local/remote origins of the Wandel Sea water masses. Finally, section 5 concludes the analysis and discusses limitations.

2. Data and methods

Between 17 April and 15 May 2015, 86 CTD profiles (labelled SN15 – XX; XX is the station number) were collected from the landfast sea ice (1.0 to 3.5 m thick) on the Wandel Sea shelf in Northeast Greenland (Figures~~-~~3 and 4). The CTD observations were carried out with a SBE-19plus CTD that was calibrated prior to the expedition, and was accurate to ±0.005°C and ±0.0005 S/m. The CTD was outfitted with a Seapoint Turbidity Meter that measured turbidity in nephelometric turbidity units (NTU). Additionally we used vertical profiles of the colored dissolved organic matter (CDOM) from an Ice Tethered Profiler (ITP) by McLane Research Laboratory that was temporarily deployed at SN15-13 from 21 April to 11 May. The ITP collected a profile every 2 hours between 3 m and 101 m depth, and was equipped with a Wetlabs ECO sensor for measuring backscatter intensity, Chlorophyll fluorescence and CDOM fluorescence for EX/EM = 370/460 nm. CDOM data was recorded approximately every 1.5 m with sensitivity of 0.28 parts per billion (ppb). Other ITP data from this temporary deployment are not used within this paper.

Four sets of complementary CTD profiles are used to provide context for the water masses we observed over the Wandel Sea shelf. CTD profiles collected in the Beaufort Sea between 225°E and 226°E ~~meridians~~ between June and October from 2002 to 2011 by ArcticNet (Figure 1) were averaged and reveal the mean summer water profile in the Beaufort Sea, which we consider the 'upstream' area. CTD profiles collected over the Wandel Sea continental slope during June and July 2015 from the research hovercraft SABVABAA during the Norwegian FRAM 2014/15 sea ice drift (Figure 2b) are used to represent the ambient water masses and compared against a CTD profile collected in August 2008 from the RV *Polarstern* [*Kattner*, 2009]. Furthermore we adopted a CTD profile taken in a rift in the 79 North Glacier in August 2009 – Figure 2b~~a~~ [*Straneo et al*., 2012].

Ice conditions over the Wandel Sea shelf, the adjoining fjords and the Greenland Sea continental slope were monitored by MODIS (Moderate Resolution Imaging Spectroradiometer – Figure 2b) and Sentinel-1 C- band SAR (C-Band Synthetic Aperture Radar – Figure 3) satellite imagery, acquired daily by the Danish Meteorological Institute (http://ocean.dmi.dk/arctic/nord.uk.php). In general, newly formed sea-ice, ice ridges, multiyear and first-year landfast sea ice, refrozen leads, large icebergs and glacier terminations are distinguishable in SAR imagery. Sea ice thickness was measured manually at each CTD station with an ice thickness tape.

Within this study we are interested in resolving the vertical thermohaline structure below the freshened surface waters, including the water layer below the lower boundary of the glacier tongue (>~90 m depth) and a warmer Atlantic-derived water layer with temperature > 0°C below ~140 m depth. Therefore we only use the 31 CTD profiles that were performed in waters deeper than 100 m (Figure ~~3~~4). Over the Wandel Sea shelf there are three regions with depths greater than 100 m. These regions are separated laterally by ~20-30 m deep shoals, but are likely connected to submarine troughs that lead towards the continental slope [*Nørgaard-Pedersen et al*., 2008].

The primary region with depth exceeding 100 m ~~Region 1~~ is located over a submarine glacial trough to the north-northeast of Station Nord~~on the outer shelf~~ that ranges in depth from 110-130 m at the tidewater glacier outlet (STN15-13 and 75) to 183 m further off-shore along the trough (STN15-63; Figure 4~~3~~). The glacial trough has been formed by the Flade Isblink Ice Cap [e.g., *Palmer et al*., 2010; *Rinne et al*., 2011]. During our surveys this area was predominantly covered by landfast multiyear sea ice (~3.5 m thick;

lighter colours in Figure 3). Several CTD stations were performed through refrozen leads that contained younger and therefore thinner sea ice (~1.5 m thick; darker colours in Figure 3). The glacial trough ~~Region 1~~ was paralleled on both sides by numerous icebergs that appeared to be grounded on the marginal lateral moraine which can significantly suppress lateral exchange with ambient water from the continental slope (Figure 3). However, lateral exchange still might be possible given the narrow glacial troughs that exist across these shallow shoals [*Nørgaard-Pedersen et al*., 2008].

Another area with depth exceeding 100 m~~Region 2~~ is located ~~over the mid shelf~~ to the northwest of Station Nord between Prinsesse Thyra and Prinsesse Margreth Islands with depths of 104/112 m (stations STN15-53/54; Figure ~~3~~4). The region was covered by ~1.2 m of sea ice that grew within a refrozen lead after it opened in August 2012 (Figure 3). We speculate that the gradual increase in depth along the CTD transect that ended at STN15-54 continues out along the trough towards the continental slope; however, no bathymetric data is available beyond STN15-54.

~~Region 3 is located to the west-southwest of Station Nord along another~~ The glacial trough to the west-southwest of Station Nord ~~on the inner shelf that extends~~ from the glacial outlet of the Flade Isblink ice cap to the west of Prinsesse Dagmar Island also exceeds 100 m depth (Figure 4a~~3~~). During our field work the glacier was grounded at ~35-40 m depth. The trough extending from this outlet glacier quickly reached depths of ~100 m (STN15-35) and reached a maximum depth of 127 m (STN15-79). During the field campaign this region was covered with a mix of first year (~1.2 m thick) and multiyear sea ice (~3 m thick), with icebergs and an ice island frozen within the fast ice (Figure 3) that corresponds to the typical ice conditions over this area. D~~Region 3 was ice-free d~~uring August 2014 (Figure 2) as well as during August 2010-2012 this region was ice-free (http://ocean.dmi.dk/arctic/nord.uk.php).

3. Results

3.1. Water mass structure

The water column over the Wandel Sea shelf shows six distinct layers (Figure 54). The layer immediately below the ice (~1.5–5 m) was relatively fresh (salinity of 16-21; Figure 54) as a result of summer snow/sea ice melt water and freshwater from the glacial runoff [*Bendtsen et al*., 2017]. Several stations had extremely fresh surface waters (salinity of 1-12; Figure 54) that appeared to be part of under-ice ponds [e.g. *Eicken,* 1994; *Flocco et al.,* 2015] comprised of melt water trapped in pockets below the multiyear landfast ice. This surface layer freshened during the melt season and was observed to have salinities of 1-8 during CTD transects in August 2015 [~~*Jørgen*~~ *Bendtsen et al.,* ~~*, pers. comm.,*~~ 2017~~6~~]. The sub-surface halocline layer is characterised by a strong vertical salinity gradient (salinity 1 m^{-1}) down to 15 m depth (Figure 54). The sub-surface halocline separated the fresh surface waters from a layer with weak vertical salinity gradients (salinity 30 to 31.2) and water near the freezing point (blue dashed line Figure 54) that reached to ~65 m depth (Figure 54). *Shimada et al.,* [2005] identified this layer in the Canada Basin and referred to it as a "cold halostad", thus over the Wandel Sea shelf we refer to this layer as the "Halostad" (Figure 54, Table 1).

Below the Halostad (below 75 m depth), temperatures increased steadily through the Halocline (with salinity centered around 33) and Atlantic modified Polar Water (PrW) – Figure 54 and Table 1. The Halocline is further distinguished from the Halostad and PrW by its high vertical salinity gradient of 0.07 m^{-1} (Figure 54). Temperatures eventually exceeded 0°C (the commonly accepted upper boundary of the Atlantic layer) at ~140 m depth indicating the presence of Atlantic Water (AW) below this depth (Table 1). Atlantic modification of the Halocline is evident from the increase in temperature through the Halocline. Furthermore, the Halocline shows intrusions of cooler water, which is further described and discussed for tracing the shelf-slope and ocean-glacier interactions, as well as the Pacific Water (PcW) and AW outflow from the Arctic Ocean through western Fram Strait.

Comparing CTD profiles collected over the Wandel Sea shelf (solid lines) and those collected off-shelf (dashed lines) reveals substantial differences in the temperature profiles down to 180 m, and in the salinity profiles down to 110 m (Figure 54). In 2015, the Halostad and Halocline over the Wandel Sea shelf were not observed over the continental slope (Figure ~~4~~5). Moreover, the thermocline was typically 20-30 m deeper off the shelf (red dashed lines Figure 54), specifically the upper boundary of the AW was found at 170 m compared to 140 m on the shelf. We also present a CTD profile collected on the upper continental slope in 2008 (dot lines in Figure 54), which reveal little variability in the water mass structure between 2008 and 2015 and indicate that the off-shelf water mass structure is characterized by a colder, thicker and more saline Halostad that is derived from the Lower Halocline in the Nansen Basin [*Rudels et al*., 1996]. We note, however, that the synoptic, seasonal and interannual variability can be significant [e.g., *Falck et al*., 2005] making it difficult to interpret the snapshot data from the Wandel Sea continental slope, while this analysis appears important and plausible~~.~~

3.2. CTD clustering

3.2.1. *Methods of CTD clustering*

In the following, we focus on the water layer below the sub-surface Halocline, comprised of the Halostad, Halocline, PrW and AW layers (Figures ~~4~~5-7~~6~~, Table 1). The 31 CTD profiles with depths greater than 100 m were subdivided into clusters according to their temperature-salinity (*TS*) curves and their variability in the *TS* space (Figures 4b, ~~5~~6 and 7~~6~~ and Table 2). The clustering was conducted to assess the origin of water masses, and to identify the shelf-slope and ocean-glacier interactions. For clustering we use the following criteria. (i) For the salinity range 30 < S < 31.2 (~15-65 m depth; Halostad; gray shaded area Figure 6~~5~~) we differentiate profiles based on their proximity to the freezing temperature (blue dashed line Figure 6~~5~~), which indicates how the water thermal properties have been modified. (ii) For the salinity range 31.2 < S < 33.5 (~65-90 m depth; upper Halocline; green shaded area Figures 6~~5~~ and 7~~6~~) we differentiate clusters based on the appearance of distinctive thermohaline intrusions within the TS curves. These intrusions increase the TS variability and disrupt the initially smooth TS curves, which indicate interaction between ambient water masses. These features have been used to trace the origin and pathways of water masses in the Arctic Ocean [e.g., *Walsh and Carmack*, 2003; *Rudels et al*., 1994; 2005; *Woodgate et al*., 2007] and identify shelf-glacier interactions [*Jenkins*, 1999~~8~~; *Stevens et al*., 2016~~5~~]. (iii) For the salinity range > 33.5 (> 90 m depth; low Halocline; pink shaded area; Figures 6~~5~~ and 7~~6~~) we use the appearance of thermohaline intrusions and the slope of the mixing line to differentiate the clusters (Figures 7d and 7e~~6~~). The displacement of the mixing line indicates ~~an external source of heat and/or salt is present and suggests a new mixing end member~~ the thermodynamic "meltwater" end member [e.g., *Jenkins*, 1999; *Straneo et al*., 2012; *Wilson and Straneo*, 2015].

The intrusions along isohalines suggest isopycnal interleaving occurs within the area (Figures 6~~5~~b and 7~~6~~c). Thus, one along-isopycnal standard deviation of the mean temperature and salinity was employed to estimate the efficiency of intrusive activity for every 0.1 kg m^{-3} interval of the potential density. All TS curves exceeding ±1 standard deviation at more than 50% of the 0.1 kg m^{-3} intervals were added to the different clusters based on the prescribed salinity range. We also defined a “transit” cluster (Figure 7~~6~~b~~a~~) showing weak thermohaline intrusions below one standard deviation of the mean.

Based on our criteria, all CTD profiles ≥ 100 m depth were subdivided into five clusters (Table 2 and Figures 4b, 6 and 7).

3.2.2. *Description of clusters*

~~Based on our criteria, all CTD profiles ≥ 100 m depth were subdivided into five clusters (Table 2).~~ Here we assess the main patterns of ~~these~~ clusters putting them in the context of their geographical location on the Wandel Sea shelf and the sea-ice features.

Cluster I is comprised of the nine CTD stations ~~with depths greater than 100 m~~ occupied (i) along the glacial trough to the west-southwest of Station Nord and (ii) between Prinsesse Thyra and Prinsesse Margreth Islands ~~in Regions 2 and 3~~ (SN15-31/35/53/54/79-83; Figures 4b and ~~7~~6a). This cluster is distinguished by two features: (i) a relatively warm Halostad overlying the Halocline above 65 m (30 < *S* < 31.2) and (ii) smooth *TS* curves through the underlying water column (*S* > 31.2) that appear to be unaffected by intrusive activity (Figure 6a~~45~~). ~~For example, all stations from Region 3 exceeded the potential freezing temperature by ~0.1°C, while both stations from Region 2 show a similar regularity, but only exceed the potential freezing temperature by ~0.03°C (gray shaded area; Figure 5a). In contrast, all stations from Clusters II-V for the salinity/depth range of 30-31.2/20-65 m show temperatures that are relatively close to the potential temperature of freezing throughout the Halostad (gray shaded area; Figure 5b). We also note that t~~The highest temperature offset from the potential freezing temperature is associated with CTD profiles from the glacial trough~~Region 3~~, which was ice-free during the preceding summer (Figure 2b) and therefore warmed through solar heating. Region between islands ~~2~~ was most recently ice-free during August 2013 (not shown), which likely led to the creation of a relatively warm subsurface layer. Thus, we subsequently refer to Cluster I as the "open water" cluster.

Cluster II (6 stations: SN15-8-11/66/68; Figures 4b, 6b and 7a) is characterised by smooth *TS* curves slightly affected by intrusive activity (Figure 7~~6~~a), with water near the potential freezing temperature in the Halostad ($S < 31.2$; gray shading in Figure 6~~5~~b). ~~Within the Halocline, between salinities of 31.2 and 33.5 (Figure 6a, green shading) all profiles from this cluster are relatively warm, exceeding the mean curve by up to 1.5 standard deviations or 0.07°C (for σ_0 = 26 kg m^{-3}). In contrast, for $S > 33.5$ this cluster is almost at the mean value (Figure 6a, pink shading).~~ Stations from this cluster occupy the ~~outer-shelf area (Region 1) near the~~ middle of the glacial trough to the north of Station Nord and were covered by multiyear landfast ice during our field program. In the following we assume that Cluster II represents the background oceanographic conditions over the Wandel Sea shelf, and subsequently refer to this group as the "basic" cluster.

Cluster III (6 stations: SN15-6/7/58/59/67/71; Figures 4b, 6b and 7b) is characterized by temperatures that remain within 1 standard deviation through salinities between 31.2 and 33.5 (green shaded area, Figures 6b~~5~~ and 7~~6a~~b), except for two profiles that deviate from the mean by -0.1 to~~÷~~ -0.2°C along the 26.9±0.1 kg m^{-3} isopycnal. In general, stations from Cluster III occupy almost the same area as

Cluster II (Figure 4b~~7~~) and represent the transition from Cluster II, with smooth *TS* curves, to Cluster IV, strongly impacted by intrusive activity. Thus, we refer to this cluster as the “transit” cluster.

Cluster IV (6 stations: SN15-62-65/69/70; Figures 4b, 6b and 7c) profiles display the most significant intrusive activity within the Halocline between salinities of 31.2 and 33.5 (Figures 6~~5~~b and 7~~6~~c). Within this range all *TS* curves show negative temperature anomalies greater than one standard deviation for at least half of the 0.1 kg m^{-3} intervals (Figure 7~~6~~c~~a~~). In contrast, the profiles from this cluster have positive temperature anomalies of about one standard deviation throughout the underlying water where $S >$ 33.5. Profiles from this cluster were taken over the compact area on the eastern flank of the glacial trough on the Wandel Sea outer shelf (Figure 4b~~7~~) and are the closest profiles to the continental slope. Hereafter we refer to these stations as the “intrusive” cluster.

Cluster V (4 stations: SN15-13/72/73/75; Figures 4b, 6b and 7d) is characterized by profiles that (i) show exceptionally strong intrusive activity in the *TS* plot for $33.5 < S < 33.85$ (90-100 m depth) and (ii) comprise a new mixing line for the underlying water layer ($S > 33.85$, >100 m depth) which is remarkably different from the ambient Clusters II-IV (Figures 7d and 7e~~6~~). For stations SN15-13/72/75, thermohaline intrusions show density-compensated negative salinity/temperature anomalies of up to -0.03/-0.32°C, and exceed the mean by more than two standard deviations. Station SN15-73 shows smaller intrusions, but they still exceed the mean by about one standard deviation. For $S > 33.9$, profiles from this cluster align with a distinct mixing line that is shifted towards lower temperatures relative to the ambient profiles. Profiles from this cluster were collected near the front of the glacial tongue, thus we refer to this cluster as the “glacier” cluster.

4. Discussion

Below we discuss the potential origin and modifications of the water masses in ~~each of the five~~ clusters II, IV and V we have identified over the Wandel Sea shelf. We also use our findings to trace the

Arctic Ocean outflow through western Fram Strait, putting our results into the context of upstream observations in the Canada Basin and downstream observations in the Northeast Water Polynya (NEW).

4.1. Shelf water i~~I~~nteraction with tidewater glacier

We speculate that cluster V shows features that we attribute to the ocean-glacier interaction. These are (i) the abnormal intrusive activity at the base of the Halocline and (ii) the transition of profiles in the *TS* space towards a new mixing line for the underlying Atlantic modified PrW at the glacier front (Figures 7d and 7e~~6~~). The ambient water from Clusters II-IV exhibits a background mixing line between the Halocline and AW (Figure 6~~5~~b) which seems to be unaffected by the ocean-glacier interaction. During summer, significant surface glacial runoff provides a new end-member to this mixture. However, during winter there is no surface glacial runoff, and subglacial runoff is negligible, as confirmed by our CTD profiles during April and May that show no surface salinity gradient around the termination of the glacier. Even though glacial melt water is negligible during winter, the glacier can still modify the ambient mixing line through ocean-glacier interactions as we will discuss below.

Water cools when it comes in contact with glacier ice that is colder than the *in situ* freezing point. For example, for the Ross Ice Shelf in Antarctica, *Wexler* [1960] reported the glacier ice temperature increased from -22°C at the surface to -14°C at 200 m depth and to -1.7°C at the glacier-ocean interface at ~260 m depth. For the Flade Isblink Ice Cap outlet, the cold glacier can significantly affect the water column below the floating glacier tongue, generating a new water mass that can be colder than the ambient PrW modified by interaction with the underlying warm AW. The sub-glacier freshwater discharge can also reduce the salinity of this water mass; however, the sub-glacier discharge is likely negligible during winter. For the floating glacier, a lateral interaction between the water below the glacier tongue and the Atlantic-modified PrW can (i) give rise to the intrusions we observed at the base of the Halocline layer and (ii) modify the background mixing line towards colder temperatures as also observed (Figures 6b~~5~~ and 7d~~6~~).

Similar intrusive interleavings at the front of a tidewater glacier were reported by *Jenkins* [1999~~8~~], *Mayer et al*. [2000] and *Stevens et al*. [2016~~5~~].

For station SN15-13, located ~200 m from the termination of the tidewater glacier (Figure 4b~~7~~), the CTD profile shows an intrusion of cool, turbid water between 88 and 97 m depths that caused a temperature inversion of -0.32°C and a sharp increase in the water turbidity from 0.2 to 1.5 NTU (Figure 8). A similar rapid increase in turbidity with depth was also recorded at the Helheim Glacier in southeast Greenland [*Straneo et al*., 2011]. We attribute this increase to the lower boundary of the glacier tongue at 88 m depth. In this case the turbid water can be attributed to subglacial discharge, or submarine melting of ice releasing sediments. The currents ~~water dynamics~~ (3-5 cm/s as a maximum, *Kirillov et al*., 2017) are~~is~~ too weak for resuspending the 20 m thick bottom layer. Assuming the ratio of glacier/water densities to be 0.917, we get a glacier elevation above the sea surface of ~7.5 m that corroborates with our visual estimates.

At the front of the glacier termination, the water below the depth of the glacier tongue is on average cooler by 0.28°C and less salty (~0.2) than the ambient water as measured at SN15-09 (Cluster II; Figure 8), suggesting a lateral heat flux along with an insignificant sub-glacier fresh water discharge in winter and/or a remnant of the larger discharge during summer. We suggest that interaction between the ambient shelf water and water below the glacier tongue, modified in direct contact with glacier ice, deflects the mixing line between the Halocline and AW in the *TS* space towards a lower temperature and, to a lesser extent, to lower salinity values.

On the stations in cluster V, taken close to the tidewater glacier outlet, intrusions of colder, less saline water are observed around 90 m depth, which is the estimated lower boundary of the floating ice tongue. The water circulating below the glacier is initially warmer than the *in situ* freezing point of seawater and will be cooled as it gets in contact with the bottom of the glacier. The lost heat is partly used to melt ice and partly conducted into the glacier, increasing its temperature. Here we assume that the largest part of the heat goes to melting and we presently ignore the fraction of heat conducted into the glacier. We also ignore all other freshwater sources, e.g. runoff and seasonal ice melt, except that due to melting of the glacier by ocean heat from below. 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 terminus. 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.

To describe the interactions occurring below the floating glacier to the first order we then assume that all heat lost by the water parcel is used to melt ice. The addition of meltwater leads to a salinity reduction ΔS that can be estimated from:

$$\cancel{\Delta S = \frac{S\frac{c_p \Delta T}{L}}{\left(1 - \frac{c_p \Delta T}{L}\right)}} \Delta S = \frac{S}{\left(\frac{L}{c_p \Delta T} - 1\right)}$$

Here $c_p = 3980$ J°C^{-1}kg^{-1} is the heat capacity of sea-water and $L = 334500$ Jkg^{-1} is the latent heat of melting. ΔT is the temperature reduction and S is the salinity of the water parcel re-emerging from underneath the glacier.

We do not have observations from below the floating glacier and we have to make assumptions both about the initial characteristics of the water entering below the glacier and the cooling and reduction of the salinity that occur by interaction with the glacier. The salinity of the water re-entering the water column from below the glacier is $S \sim 33.65$ and the observed temperature reduction, compared to the ambient profiles, is $\Delta T \sim 0.3$°C (Figures 4b and 6~~5~~b~~ and 7~~d). We know that the initial salinity then has to be higher than 33.65. Looking at the ambient profiles (Figure 5~~4~~) we note that the mean temperature of the water that could possibly enter beneath the glacier is about -0.8°C. Assuming it is cooled to freezing temperature, ΔT is 1°C and ΔS becomes ~0.4. This gives an initial salinity of 34.05 to the water entering below the glacier.

However, the observed cold intrusions are not at the freezing point, instead they are warmer, around −1.4°C (Figure 8). This could indicate that the water entering below the glacier is not cooled to the freezing point, but only by ~0.3°C. The initial salinity would then be 33.8 rather than 34.05. Another possibility is that the cold water penetrates isopycnally into the water column and becomes warmer and more saline by mixing with ambient water. Assuming that the intrusions are isopycnal, the changes in temperature and salinity due to mixing becomes:

$$\alpha \Delta \mathrm{T} = \beta \Delta S$$

Here α=0.4×10^{-4} $^{\circ}$K^{-1} is the coefficient for the heat expansion around −1ºC and β=8×10^{-4} psu^{-1} is the coefficient of salt contraction. A temperature change of 0.5°C then corresponds to a salinity change of 0.025, making the salinity at the freezing point of 33.625, close to the observed 33.65 at the intrusion and giving the initial salinity as 34.025. This suggests that the intrusions observed on the stations close to the tidewater glacier outlet (Cluster V) might derive from the outflow of colder, less saline water created under the floating ice tongue due to interactions between the glacier and the underlying water masses.

4.2. Shelf water ~~I~~interaction with ambient water from the continental slope

We use the occurrence of intrusive interleaving as a tracer for the shelf-slope interaction. The intrusive Halocline from Cluster IV was observed to the north of Station Nord~~over the outer shelf~~ (Figure 4b~~7~~) adjacent to the Greenland continental slope, where a water mass with different thermohaline properties is located (Figure 5~~4~~). The intrusions are indications of isopycnal interaction between the Atlantic-modified Halocline occupied over the Wandel Sea shelf and a cooler PrW observed over the Wandel Sea continental slope (Figure 5~~4~~). Within the depth range of the Halocline (~65-100 m), the cooler PrW is likely maintained by a weakened upward heat flux from the deepened AW in the off-shelf area. Over the Wandel Sea shelf, the upper AW boundary was recorded at ~140 m, while in June-July 2015 and August 2008 it was ~30 m deeper over the adjacent continental slope (Figure 5~~4~~). We note, however, that the water mass structure over the continental slope of Northeast Greenland shows significant interannual variability [e.g., *Falck et al.,* 2005]. Overall, the distinct difference between the on-shelf and off-shelf water mass structure (Figure 5~~4~~) suggests their different origins, which are further discussed in section 4.3.

In the following we speculate that the intrusive Halocline from Cluster IV is generated by interaction between the Atlantic-modified shelf Halocline (Cluster II) and the PrW from the continental slope as shown in Figure 9a. We suggest that this interaction is isopycnal because all intrusions are density compensated. For the Halocline layer over the southern Wandel Sea continental slope, *Rudels et al*. [2005] reported an intrusive interleaving conditioned by isopycnal interaction between relatively warm Halocline water from the upper continental slope, and cold PrW from the lower continental slope.

For further interpretation of our results on the shelf-slope interaction we include 184 CTD profiles taken between 1992 and 1993 in the NEW area [*Bignami and Hopkins*, 1997; *Budéus et al*., 1997; *Falck,* 2001], which is downstream from the Wandel Sea shelf (Figures 1 and 2b). The *TS* curves from the NEW area show two distinct modes: (i) the polynya (shelf) mode, which is similar to the "basic" Cluster II derived for the Wandel Sea shelf (Figure 4~~5~~b, 7a~~6~~ and dark blue lines in Figure 9a) except for a slightly colder (~0.05°C) and saltier (~1) low Halostad, and (ii) the continental slope mode, which within the salinity range of the Wandel Sea shelf Halocline (31.2-34) shows a completely different shape of the *TS* curve (red lines in Figure 9a). Specifically the *TS* line of the continental slope mode extends linearly through the Halostad to salinity of ~34 (red dashed line in Figure 9a; red rectangles in Figure 9b), maintaining temperatures relatively close to the surface freezing temperature (blue dashed line Figure 9b).

For the NEW area, the remarkable difference between the polynya (shelf mode) and the continental slope mode was also reported by *Straneo et al*. [2012] and *Wilson and Straneo* [2015], with a *TS* structure similar to the one presented in Figure 9 (Figure 3 from *Wilson and Straneo*, 2015). Moreover, for the 79N glacier outlet (Figure 2b), *Straneo et al*. [2012] used the upper continental slope CTDs as ambient stations and compared them to CTD profiles taken through a rift in the floating glacier tongue (see Figure 2b for the glacier station position). For the water layer at ~40-90 m depth, they reported ambient water that was saltier than water below the glacier tongue by ~1-2, attributing this difference to the sub-glacier water discharge.

We note, however, that this freshening is of the same magnitude as the salinity difference between the shelf Halostad/Halocline and the continental slope PrW (Figure 9). Thus, freshening reported by *Straneo et al*. [2012] could be alternatively explained by the occurrence of the Halostad-like freshened water layer below the glacier tongue.

In the following sections 4.3 and 4.4, we use the differences between the on-shelf and off-shelf water mass structures and the similarities between the Wandel Sea and NEW areas to trace the origin of the Halostad, Halocline and AW in the Wandel Sea and their modification along the northeast Greenland coast.

4.3. Tracing the origin of the Wandel Sea Halostad, Halocline and AW: Local source

The distinct difference between the on-shelf and off-shelf water mass structure and disposition suggests they have different origins and/or pathways to the Wandel Sea shelf and continental slope. The occurrence of the shelf Halostad can be explained by local freshening by summer snow/sea-ice melt water and freshwater from the glacier runoff. In turn, the uplifted on-shelf Atlantic-modified PrW and AW can originate from local modifications due to upwelling of AW over the Wandel Sea continental slope.

The under-ice surface layer over the Wandel Sea shelf is significantly freshened, potentially providing a source of freshwater for the freshened Halostad over the shelf if vertical mixing overcomes the salinity (density) stratified sub-surface halocline as was suggested for NEW by *Bignami and Hopkins* [1997]. Among the Arctic shelves, the Wandel Sea sub-surface halocline shows exceptionally strong vertical stratification with salinity increasing from 18 to 30 across a ~10 m thick sub-surface halocline layer during winter (Figure 54). This is comparable to the Laptev Sea shelf where strong salinity stratification is maintained by the river runoff from the Lena River, the second largest river flowing into the Arctic Ocean [e.g., *Dmitrenko et al*., 2010]. *Dmitrenko et al*. [2012] showed that significant velocity shear over the Laptev Sea shelf, attributed to the lunar semiduirnal baroclinic internal tide M2 with velocity ~15 cm/s at 11 m and ~7 cm/s at 19 m depth is required to transform the vertically stratified water into a locally mixed layer. In contrast, over the Wandel Sea shelf velocities hardly exceed 3-5 cm s^{-1}, and the most energetic M2 tidal currents are weak, decreasing from ~2 cm/s beneath the ice to ~1 cm/s below 60 m depth [~~*Sergei*~~ *Kirillov* *et al.*, ~~*, pers. comm.,*~~ 201~~6~~7]. Moreover, the multiyear landfast ice cover over the Wandel Sea shelf precludes the wind stress from vertically mixing the stratified water column.

Hypothetically, the wind-driven upwelling of the Atlantic-modified PrW and AW over the continental slope can result in uplift of the water masses over the outer shelf. In this case, however, the shallowing of the Atlantic-modified PrW and the upper boundary of AW is accompanied by on-shelf inflow of the deeper and saltier water from the continental slope. In contrast, the Atlantic-modified Halocline on the shelf is less salty compared to ambient water from the continental slope by ~1-2.

In the following we discuss our results in the context of upstream observations in the Canada Basin (e.g., Figure 10) and downstream observations in the NEW region.

4.4. Tracing the origin of the Wandel Sea Halostad, Halocline and AW: Far field advection

We suggest that the on-shelf Halostad and the associated Halocline can be advected from the remote upstream areas where sources of fresh water exist. Similarly, as with the shelf Halostad, the shallowed AW layer recorded over the Wandel Sea shelf and the deepened AW layer found over the continental slope should be attributed to the different branches of the AW outflow from the Arctic Ocean through western Fram Strait.

The East Greenland Current carries the Arctic Ocean outflow through western Fram Strait southward along the Greenland shelf and continental slope – Figure 1 [e.g., *Rudels et al*., 2002; *Jeansson et al*., 2008]. It transports cold, low salinity Polar surface waters with $\sigma_0 \leq 27.7$ kg m^{-3} [*Rudels et al*., 2002] that are comprised of the river runoff and net precipitation water, but also of the less saline PcW that enters the Arctic Ocean through Bering Strait [*Jones et al*., 1998, 2003, 2008; *Rudels et al*., 2002; *Falck et al*., 2005; *de Steur et al*., 2009; *Sutherland et al*., 2009] – Figure 1. PcW within the Arctic Ocean is generally assigned to water with $S \leq 33$ [*von Appen and Pickart*, 2012] and has both a summer and winter signature based on its formation. The summer PcW with temperatures above -1.2°C and salinities between 31 and 32

[*Steele et al*., 2004] is usually comprised of the Chukchi Summer Water [*Woodgate et al*., 2005] and the Alaskan Coastal Water [*Pickart et al*., 2005]. Below the summer PcW is a layer of winter PcW that can be as cold as -1.45°C and forms during sea ice formation within the Bering and Chukchi Seas [*Jones and Anderson*, 1986; *Weingartner et al*., 1998; *Pickart et al*., 2005].

It has been shown that the subsurface layer over the eastern Greenland coast is comprised of the PcW outflow from the Arctic Ocean [*Jones et al*., 1998, 2003, 2008; *Falck*, 2001; *Falck et al*., 2005; *Jeansson et al*., 2008; *Sutherland et al*., 2009]. For the 1993 observations over the NEW shelf area, in the subsurface Halostad layer down to ~80 m depth, an average of about 90% is found to have Pacific origin [*Falck*, 2001]. This result by *Falck* [2001] brought a different mechanism of the Halostad formation to light. In contrast to *Bignami and Hopkins* [1997], *Falck* [2001] insists on an upstream Pacific source for the Halostad water and underlying Halocline, rather than a local origin.

Upstream over the Canada Basin, PcW impacts the halocline structure, producing a double halocline with a "cold Halostad" formed by the volumetric injection of the winter PcW that overlies Low Halocline Water of the Eurasian Basin origin [*McLaughlin et al*., 2004; *Shimada et al*., 2005]. The salinity range of the cold Halostad in the Canada Basin occupies $31.5 < S < 33.5$ with the lowest temperature of ~ -1.7°C at the base of the Halostad indicating the winter PcW [*McLaughlin et al*., 2004; *Shimada et al*., 2005]. This water mass structure resembles that for the eastern Beaufort Sea continental slope (Figure 10).

In general, the Halostad structure over the Canada Basin and adjoining continental margin is similar to that recorded over the Wandel Sea shelf (Figure 54). However, over the Wandel Sea shelf the Halostad is cooler and fresher (Figure 10c) occupying a salinity range of $30.0 < S < 31.5$. The Wandel Sea Halostad is also shallower (15-65 m depth versus ~50-200 for the Canada Basin). The different salinity range of the Halostad in the Wandel Sea and Canada Basin suggests that significant modifications occurred during transit of the winter PcW from the Bering and Chukchi Seas to the Wandel Sea. It seems that the winter PcW is modified by vertical mixing with overlaying summer PcW and/or river runoff accumulated in the Canada Basin. For example, *Jones et al*. [2008] revealed that over the northeast Greenland coast at ~81°N, the PcW fraction is comparable with the river water fraction. Moreover, water from the Siberian shelves, especially the Laptev Sea shelf also has the same salinity and temperature range and can mix into and cool the summer PcW [e.g., *Dmitrenko et al*., 2011]. This assumes that the river water impacts a Wandel Sea Halostad initially comprised of the winter PcW.

The remote origin of the Halostad is also confirmed by the elevated values of the CDOM fluorescence through the Halostad layer at station SN15-13 (Figure 8). The CDOM fluorescence is a good tracer of the Arctic Ocean terrigenous organic matter primarily attributed to the Eurasian and American continental runoff water [e.g., *Granskog et al*., 2012] as well as to interactions with sediments on the Arctic shelves [e.g., *Guéguen et al*., 2007]. The CDOM fluorescence maxima in the Halostad at station SN15-13 is consistent with results from the Canada Basin where this maxima is attributed to the winter PcW [e.g., *Guéguen et al*., 2007] and the continental river runoff water [e.g., *Granskog et al*., 2012]. For the downstream NEW area, *Amon et al*. [2003] also reported the intermediate maxima of the CDOM fluorescence through the shelf Halostad layer (Figure 9a from *Amon et al*., 2003). Overall, this confirms the remote origin of the Halostad layer over the Wandel Sea shelf and strengthens our discussion on the modification of the Pacific-derived Halostad by river runoff while en route from the Canada Basin to Fram Strait.

As the Halocline and AW move along the Canada Basin margins toward northern Greenland, they ascend in the water column from 100-200 m and 220-320 m in the Canada Basin [*McLaughlin et al*., 2004; *Shimada et al*., 2005] to 85 m and 140 m on the Wandel Sea shelf, respectively (Figure 54). Following *Rudels et al*. [2004], we speculate that this rise is due to the gradual thinning of the low salinity layer above. The thinning could be caused by the upper layer either being confined to the Beaufort Gyre or draining through the Canadian Arctic Archipelago and ultimately into Baffin Bay [*Rudels et al*., 2004]. This is consistent with a gradual shallowing of the upper boundary of AW traced by isopycnal $\sigma_0 = 27.4$ kg m^{-3} from ~230 m in the Canada Basin to ~140 m in the Wandel Sea [*Polyakov et al*., 2010].

The occurrence of the Pacific origin Halostad along the northeast Greenland coast suggests that PcW is transported southward by a narrow coastal branch of the East Greenland Current. This current also advects a shallowed AW, which likely originated from the Canada Basin branch (Figure 1). The cross-slope interaction between the coastal and off-shelf branches of the East Greenland Current gives rise to the intrusive interleaving observed over the Wandel Sea outer shelf (Figure 7~~6~~c~~a~~).

5. Summary and conclusions

The first-ever CTD observations over the Wandel Sea shelf and continental slope were collected in April-May and June-July 2015, respectively. We use CTD profiles deeper than 100 m to focus on the origin of water masses, and to identify interactions between the shelf and slope, and between the ocean and outlet glaciers entering the Wandel Sea. The stations taken on the Wandel Sea shelf and farther to the east on the Greenland slope reveal two pathways for the advected water masses, one over the shelf and one along the continental slope. The one over the slope has warm, saline AW lying below a deep, cold, less saline and fairly homogenous upper layer that is capped by low salinity surface water created by seasonal ice melt and heated by solar radiation. This suggests that AW recirculating within the Eurasian Basin (Figure 1) with the less dense upper layer initially formed by sea ice melt water are mixed into the upper part of the entering AW. In the Nansen Basin this layer is homogenized by haline convection each winter [*Rudels et al*., 1996].

The water column found on the shelf has much colder and less saline AW located closer to the surface than the AW over the slope. The AW characteristics here are similar to those observed at much greater depth in the Canada Basin, indicating that this AW has circulated around the entire deep Arctic basins and now is returning towards Fram Strait. In the Canada Basin, the AW is covered by the halocline layer and it is comprised of both Atlantic ($S \sim 34$) and Pacific derived water, especially the Pacific Winter Water, with $S \sim 33.1$ [e.g., *Jones and Anderson*, 1986], as well as other low salinity waters. These low salinity waters lie shallower than the sill depth of the Canadian Arctic Archipelago and can pass through the straits into Baffin Bay. This would cause the AW to rise in the water column as it moves along the northern Canadian coast, until it is shallow enough to flow over deeper shelves like that of the Wandel Sea.

Over the Wandel Sea shelf, the Pacific Winter Water, that was so distinct in the Canada Basin, seems to be either missing or only occupying a narrow depth range. Instead the coldest water is found in the Halostad with salinity around 31 instead of 33. The low salinity upper layer and the thick ice cover in winter preclude the local homogenization of the water column down to the Halostad. Thus, the Halostad must be advected from elsewhere. A conceivable scenario could be that most of the PcW drains out of the Arctic Ocean through the Canadian Arctic Archipelago. This likely makes the AW ascend and it would allow water from the Polar Mixed Layer, of Atlantic or Pacific origin, circulating in the Beaufort Gyre and in the Arctic basins to replace the water leaving through the straits in the archipelago and penetrate onto the shelf, creating a different upper layer above the AW.

Our findings are summarised as follows:

(i) The sub-surface (15-70 m depth) “cold Halostad” layer with salinities of 30-31.5 and associated underlying Halocline layer is a distinct feature of the Wandel Sea shelf hydrography. It does not persist over the Wandel Sea continental slope, indicating the water masses over the shelf and slope have different origins. A similar water mass structure was observed downstream in the Northeast Water Polynya area. This structure is likely maintained by the coastal branch of the Pacific Water outflow from the Arctic Ocean, modified by interaction with river runoff water over the upstream Canada Basin.

(ii) The Halocline layer centered at ~80 m (salinity of ~33) separates the Pacific-origin cold Halostad from the Polar Water, modified by interaction with warm Atlantic water outflow from the Arctic Ocean through western Fram Strait. The upper boundary of the Atlantic Water (T ~ 0°C) is recorded at ~170 m depth on the continental slope and ~30 m shallower over the adjoining shelf. This difference suggests that, as with the subsurface layer, the intermediate water over the shelf and continental slope is conditioned by different branches of the Atlantic water outflow from the Arctic Ocean.

(iii) The lateral shelf-slope interaction between on-shelf relatively warm Atlantic-modified Halocline water and off-shelf cold Polar Water gives rise to the intrusive interleaving observed over the Wandel Sea outer shelf.

(iv) At the base of the Halocline layer, cold and turbid water intrusions were recorded at the front of the tidewater glacier outlet. The temperature-salinity plots of the CTD profiles from this region show a mixing line that is deflected relative to the ambient water. Both features are likely conditioned by the ocean-glacier thermal interaction.

In summary, our analysis suggests the existence of a coastal branch of the East Greenland Current advecting Pacific Water of Arctic origin southward along the northeast Greenland coast. This is consistent with an earlier proposition by *Rudels et al*. [2004], downstream observations along the southeast coast of Greenland [e.g., *Bacon et al.,* 2002; *Sutherland and Pickart*, 2008; *Sutherland et al*. 2009] and numerical simulations [*Hu and Myers*, 2013; *Aksenov et al*., 2016]. Finally, we note that our observations were not accompanied by water sampling for determining the nitrate/phosphate relationship commonly used to trace the Pacific Water in the Arctic Ocean and Greenland Sea. This deficiency in the observational program conducted clearly shows the necessity for further research in this area using advanced methods of tracer analysis.

Acknowledgments: This study was funded by the Canada Excellence Research Chair program (SR), the Canada Research Chair program (DB), the Canada Foundation of Innovation, the National Sciences and Engineering Research Council of Canada (grant RGPIN-2014-03606, ID), the Manitoba Research and Innovation Fund, the University of Manitoba, Aarhus University, the Greenland Institute of Natural Resources, and the EU project NACLIM (grant agreement 308299, BR). We thank Ivali Lennert, Kunuk Lennert and Egon Frandsen for technical assistance in the field. We also appreciate outstanding logistical support from the Station Nord Danish military personnel. John Mortensen (Greenland Climate Research Centre) provided valuable comments on the ocean-glacier interaction. Comments and editing by Dr. John

K. Hall, the owner of the research hovercraft SABVABAA, are highly appreciated. Dr. Nils Nørgaard-Pedersen kindly provided bathymetric data used in Figure 4a~~3~~. This work is a contribution to the Arctic Science Partnership (ASP) and the ArcticNet Networks of Centres of Excellence programs. For the Wandel Sea CTD data contact ID at igor.dmitrenko@umanitoba.ca

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Tables

Table 1: The Wandel Sea water mass structure below 15 m depth

Water layer	Acronym	Property range			
		Depth, m	Temperature, °C	Salinity	σ_0, kg m^{-3}
Halostad (of Pacific origin)	-	~ 15÷65	~ -1.5 ÷ -1.75	30÷31.2	24.1÷25.1
Pacific Water	PcW	PcW comprises the Halostad			
Halocline	-	~ 65÷100	~ -1.75 ÷ -0.65	31.2÷34	25.1÷27.3
Atlantic-modified Polar Water	PrW	~100÷140	-1.15 ÷ 0	34÷34.5	27.3÷27.7
Atlantic Water	AW	>140	>0 (up to 0.3)	>34.5	>27.7

Table 2: Description of the Wandel Sea CTD clusters

Cluster #	Cluster name	Station #	Main features	Property range			
				Depth m	Temp. °C	Salinity	σ_0 kg m^{-3}
I	Open water	31, 35, 53, 54, 79-83	"Warm" Halostad	15÷65	~ -1.6	30.0÷31.2	24.2÷25
			Smooth TS curves	>65	-1.7÷-0.8	>31.2	>25
II	Basic	8-11, 66, 68	"Cold" Halostad	15÷65	-1.6÷-1.72	30.0÷31.2	24.2÷ 25
			Smooth TS curves	>65	-1.7÷-0.8	>31.2	>25
III	Transit	6, 7, 58, 59, 67, 71	Moderate intrusions with temperature anomalies < 1 standard deviation	65-90	-1.25÷-1.6	31.2÷ 33.5	25.6÷ 26.7
IV	Intrusive	62-65, 69, 70	Significant intrusions with negative temperature anomalies > 1 standard deviation	65-90	-1.25÷-1.7	31.2÷ 33.5	25.3÷26.7
V	Glacier	13, 73, 73, 75	Significant intrusions	90-100	-1.2÷-1.4	33.5÷33.85	>27.1
			Deflected mixing line	>100	>-1.2	>33.85	>27.2

Figures

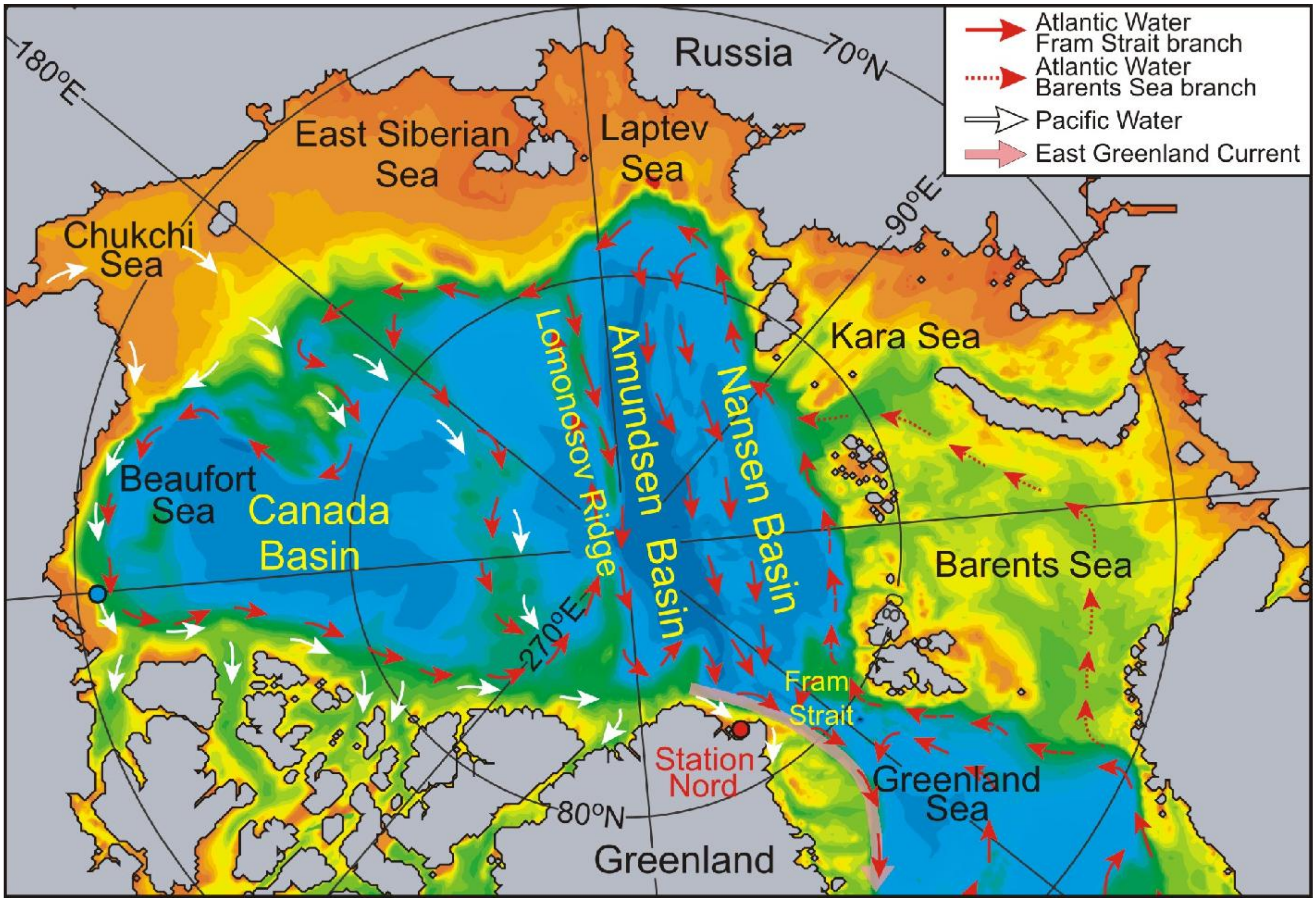


Figure 1: Schematic circulation of the Atlantic Water (AW, red arrows) and Pacific Water (PcW, white arrows) in the Arctic Ocean and adjoining Greenland Sea following *Rudels et al*. [1994], *Jones* [2001], *Rudels* [2012], and *Woodgate* [2013]. The dashed and dotted red arrows correspond to the Fram Strait and Barents Sea branches of the AW inflow, respectively. The pink arrow indicates the East Greenland Current. The red dot depicts the position of Station Nord in Northeast Greenland. The blue dot roughly identifies location where CTD profiles were collected in the Beaufort Sea.

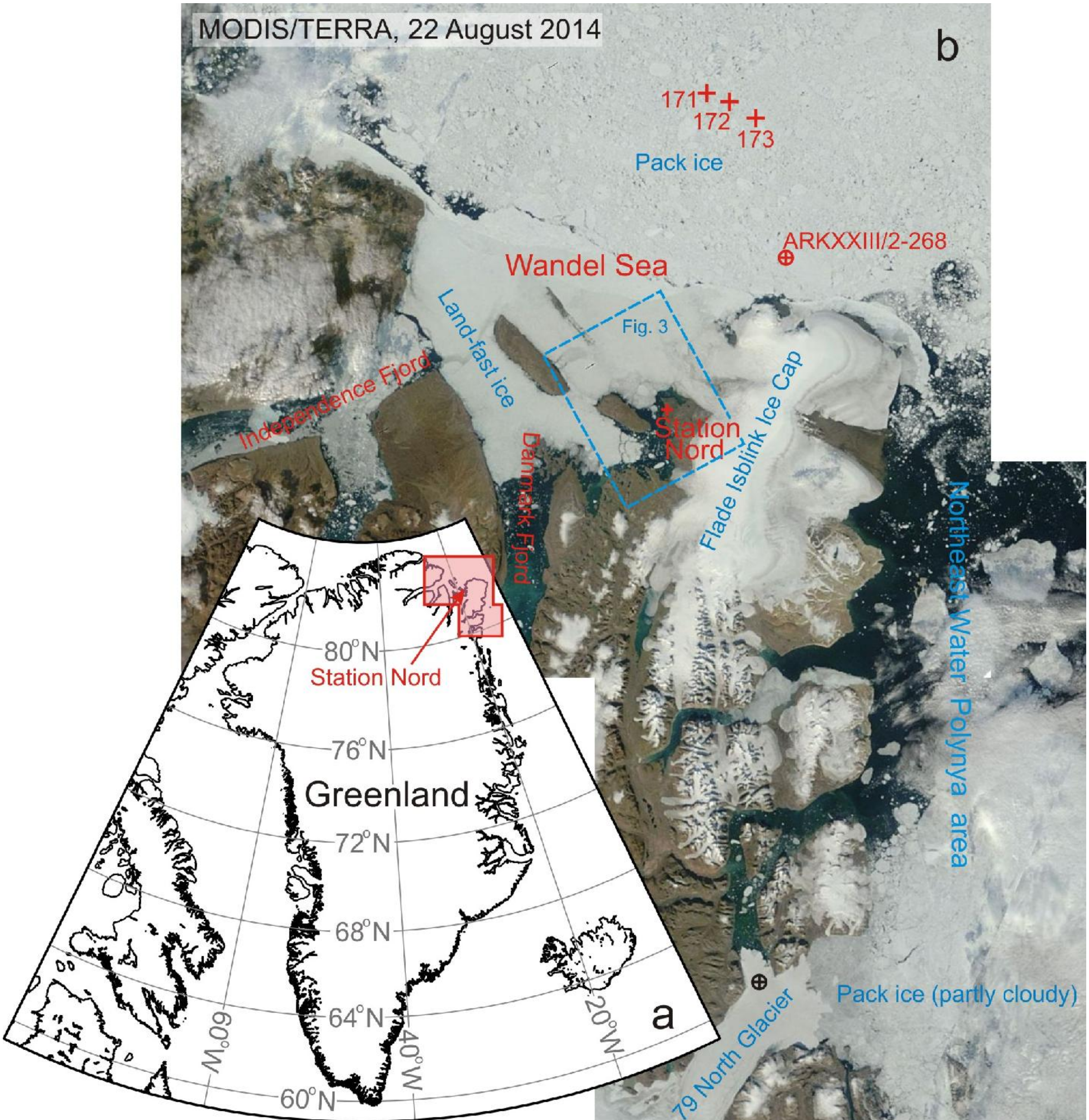


Figure 2: (**a**) Station Nord (SN) on the Greenland map. The pink shading highlights the Wandel Sea region with adjoining fjord system, Flade Isblink Ice Cap (FIIC), the Northeast Water Polynya (NEW) area and the 79 North Glacier outlet enlarged in panel (**b**). (**b**) The MODIS/TERRA satellite image from 22 August 2014 taken over the SN/FIIC/NEW area. Red and black circled crosses indicate the CTD stations occupied over the Wandel Sea outer-shelf during the ARKXXIII/2 expedition in August 2008 and in a rift in the 79 North Glacier in August 2009. Red crosses depict the CTD stations occupied in June-July 2015 over the Wandel Sea continental slope (> 1000 m depth) during the Norwegian FRAM 2014-15 sea ice drift. The dashed blue ~~rectangule~~rectangle indicates the 2015~~4~~ study area shown in Figure 3.

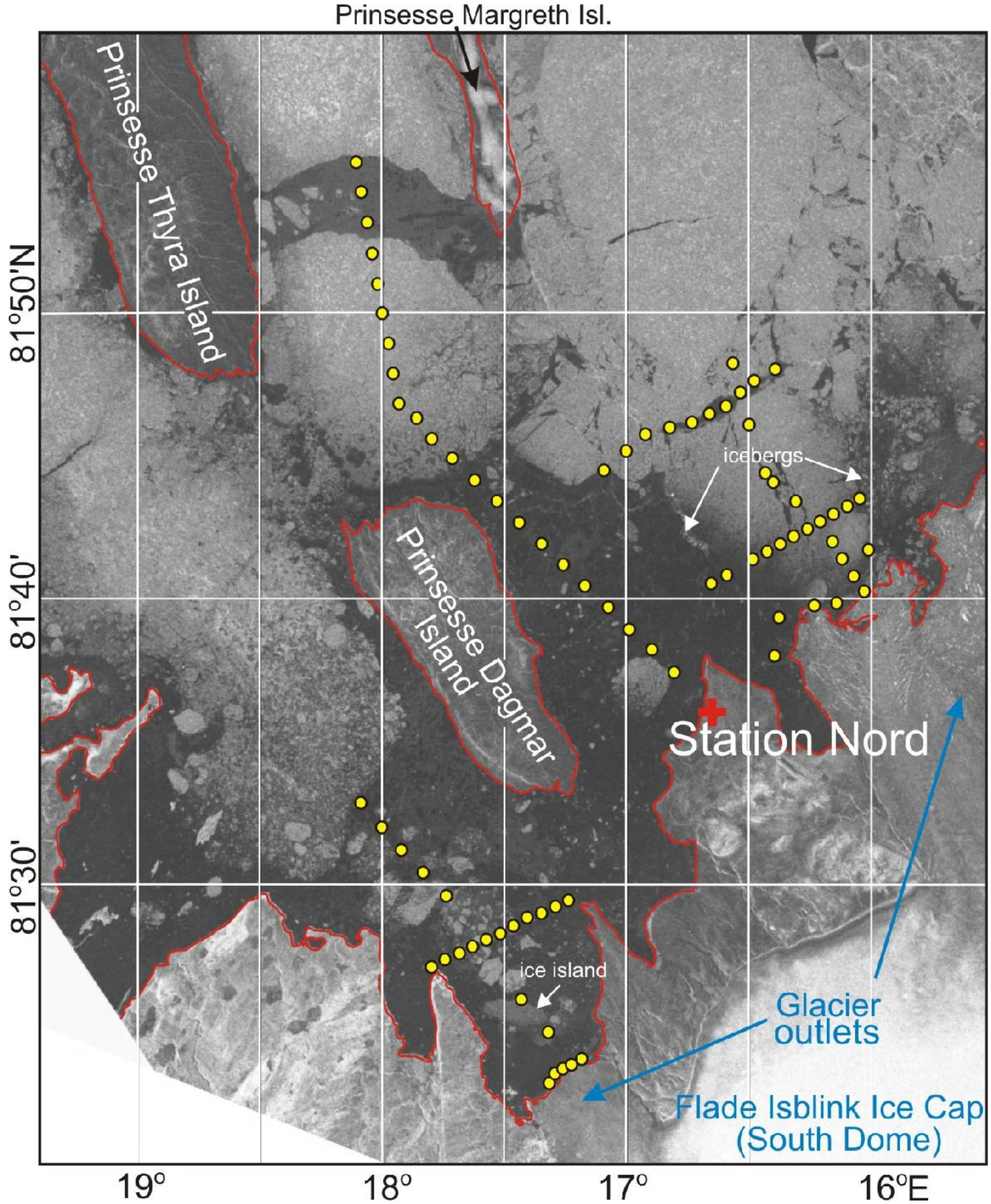
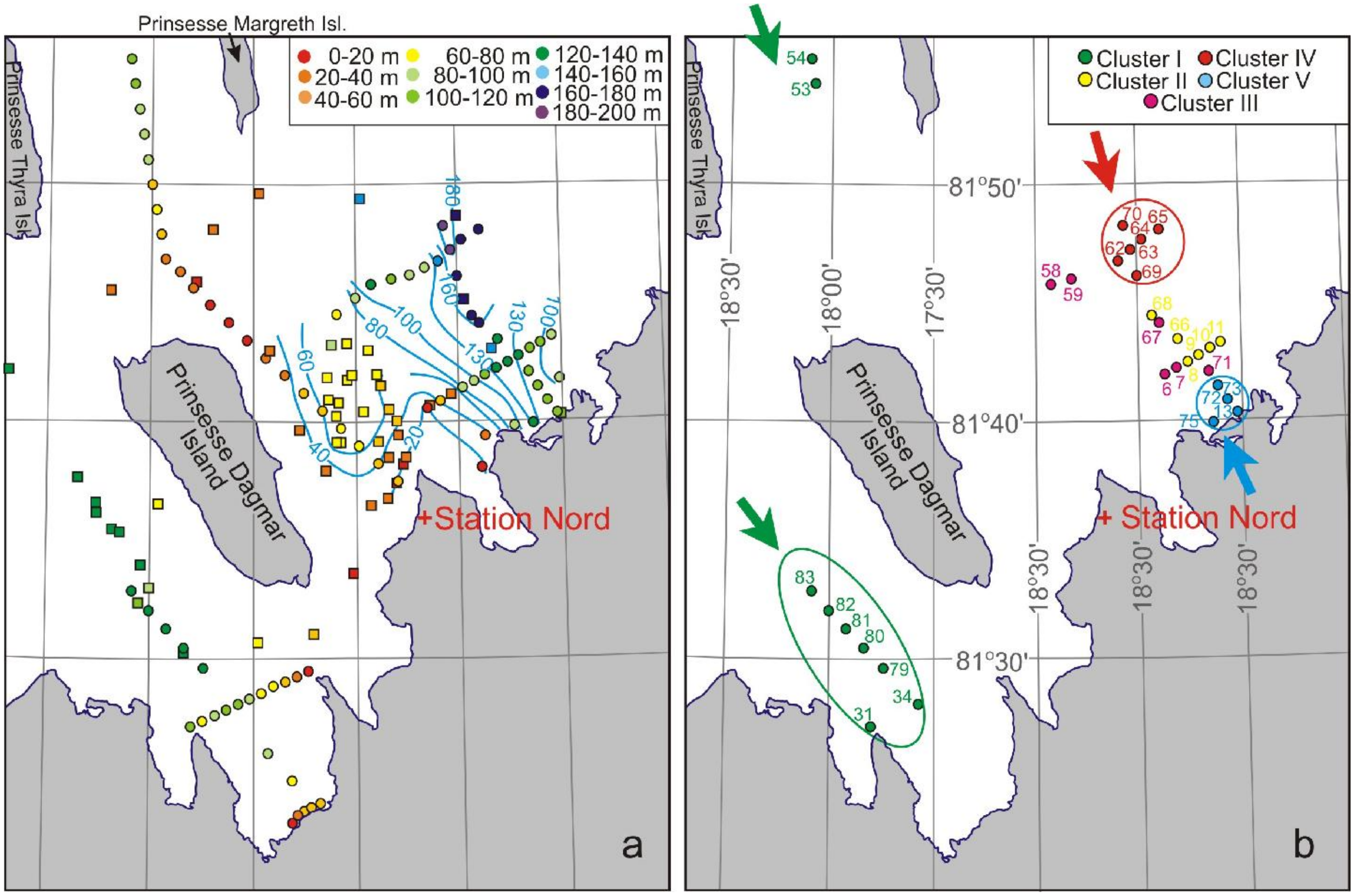


Figure 3: The Sentinel-1 C-SAR image from 2 February 2015 with the CTD stations overlaid. The dark areas along the coast are associated with first year landfast ice (< 1.8 m thick). The lighter areas indicate the multi-year landfast ice (~2 m to > 4 m thick). ~~White and black~~ Yellow circles identify stations with CTD ~~(April-May 2015) and depth (May 2006, adopted from *Nørgaard-Pedersen et al*. [2008] and April 2015)~~ measurements~~, respectively, with depths shown by color. CTD stations > 100 m deep are identified by their station numbers.~~ Blue arrows indicate the northern outlet glaciers of the Flade Isblink Ice Cap. ~~Pink/yellow/blue dashed rectangles depict regions 1/2/3, respectively, with depth exceeding 100 m. The blue contour lines show the bottom depth.~~



<u>**Figure 4**: CTD stations occupied in April-May 2015 (circles). (**a**) Depth shown by color and blue contour lines. In addition, rectangles identify stations with depth measured in May 2006 (adopted from *Nørgaard-Pedersen et al*., 2008) and April 2015. (**b**) CTD stations > 100 m depth are grouped in clusters derived from the *TS* analysis. They are identified by their station numbers. Arrows depict deep water pathways.</u>

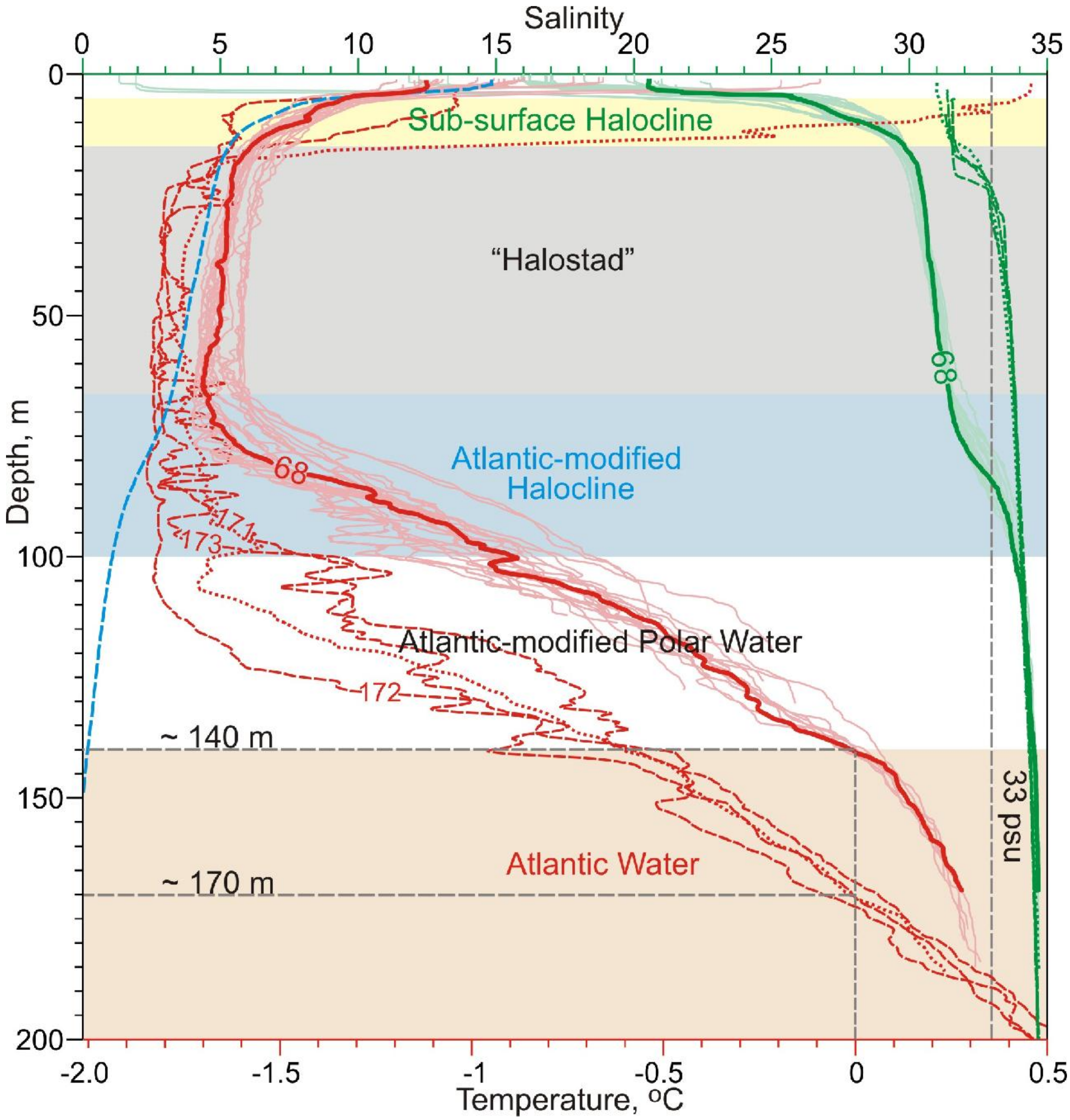


Figure ~~4~~5: Vertical distribution of temperature (red) and salinity (green) profiles over the Wandel Sea shelf (≥ 100 m depth; solid curves) from April and May 2015, over the continental slope (stations 171-173; dashed curves) from June and July 2015 from the Norwegian FRAM 2014-15 ice drift (see Figure 2b for station position) and on the Wandel Sea upper continental slope (ARKXXIII/2 268; dotted curves) from RV Polarstern on 2 August 2008 [*Kattner,* 2009]. Thick red and green lines show typical vertical profiles of salinity and temperature, respectively, for station STN15-68. The blue dashed curve is the *in situ* temperature of freezing computed using the mean SN salinity profile (not shown). ~~The yellow shading highlights sub-surface halocline. The blue shading highlights Atlantic-modified Halocline conditioned by the PcW outflow from the Arctic Ocean which comprises the overlying Halostad (gray shading). The peach shading highlights the AW outflow from the Arctic Ocean, underlying the Atlantic-modified Polar water (PrW).~~ The vertical dashed line depicts salinity of 33 that separates the PcW and AW in the western Beaufort Sea [*von Appen and Pickart*, 2012].

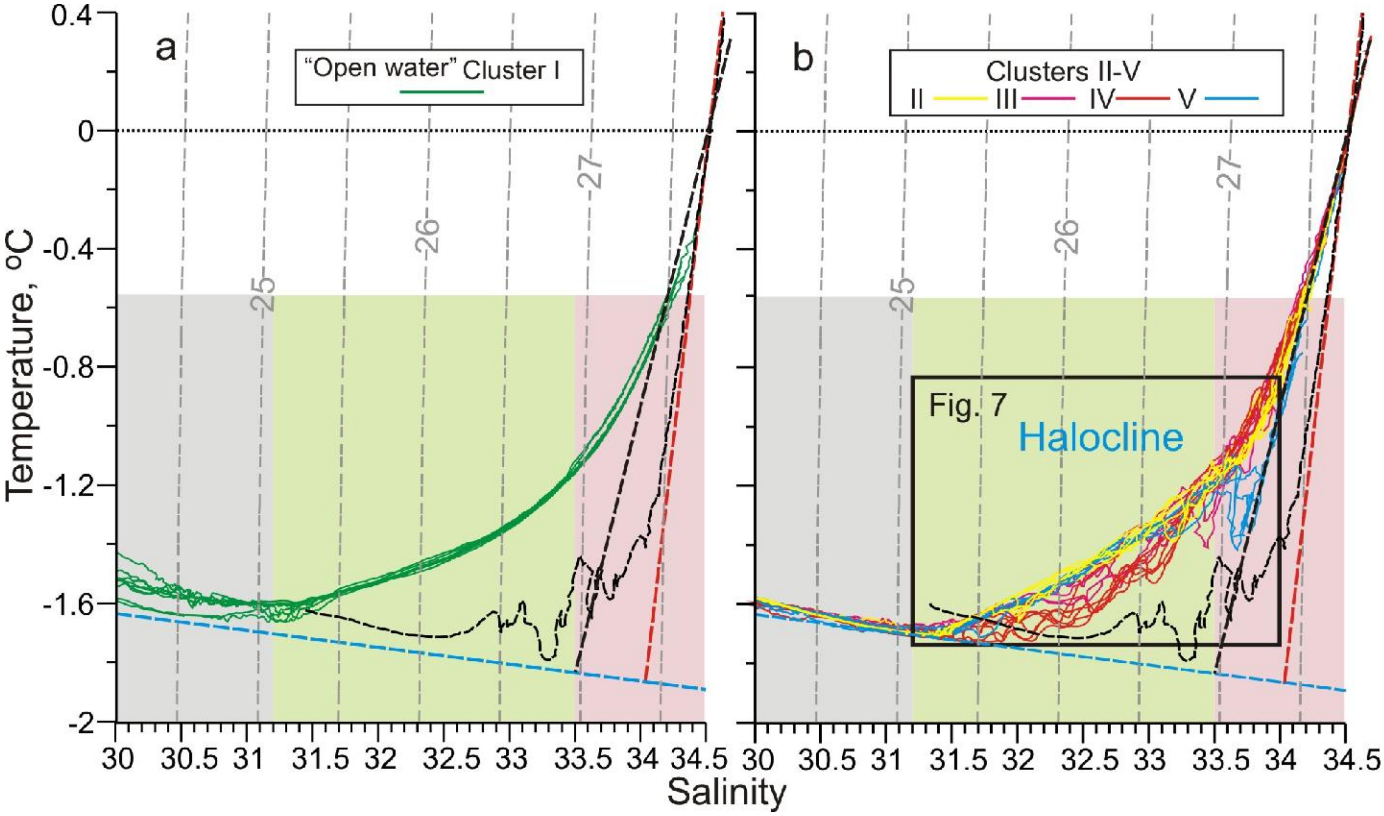


Figure 6~~5~~: *In situ* temperature and salinity curves for the CTD stations >100 m depth with σ_0 isopycnals presented (dashed grey lines; kg m^{-3}). (**a**) CTD profiles ~~from Region 2 and 3 that are~~ grouped into Cluster I "Open Water". (**b**) CTD profiles ~~from Region 1 that are~~ grouped into Clusters II–V. The halocline layer of the water column is enlarged in Figure ~~5a~~7 where Clusters II-V are distinguished. We also present an approximation of thermohaline properties for the downstream Atlantic-modified PrW over the NEW continental slope (dashed red line; adopted from *Falck*, 2001) and the profile from Station 172 over the Wandel Sea continental slope (thin black dashed line). The surface freezing temperature is also presented (dashed blue line). 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). The panels are shaded according to the corresponding water masses; gray represents the Halostad, while green and pink represent the halocline and define the salinity used for clustering.

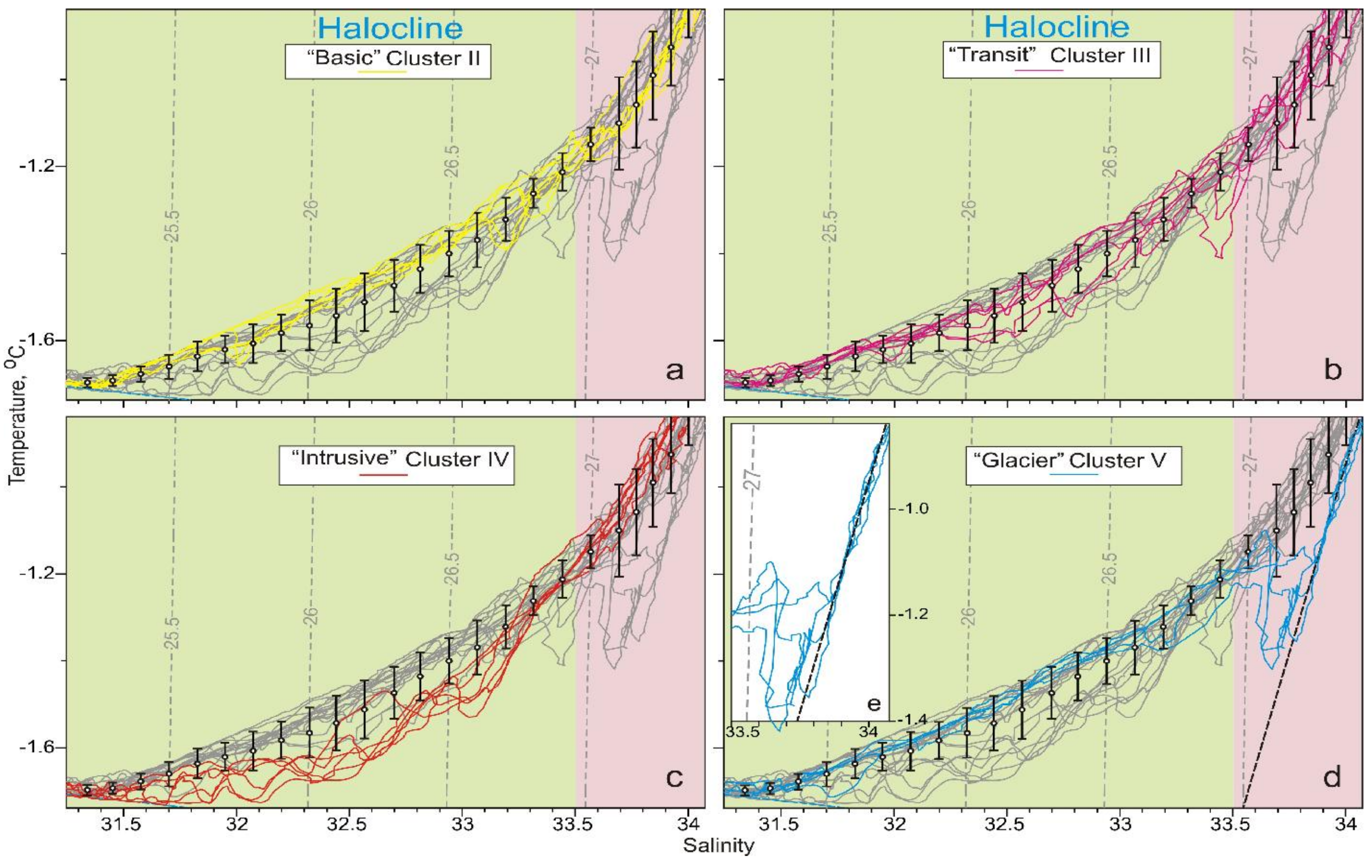


Figure 7~~6~~: ~~(a)~~ In situ temperature and salinity curves for the CTD profiles grouped into Clusters (**a**) II (yellow), (**b**) III (purple), (**c**) IV (red) and (**d**)~~–~~V (blue) overlaid over the profiles from other clusters (grey). The mean TS characteristics ±1 standard deviation (white barred dots) are presented at isopycnal intervals of 0.1 kg m^{-3}. All other designations are similar to those in Figure 6~~5~~. (**e**~~b~~) Temperature and salinity curves below the glacier depth for the CTD profiles grouped into Cluster V.

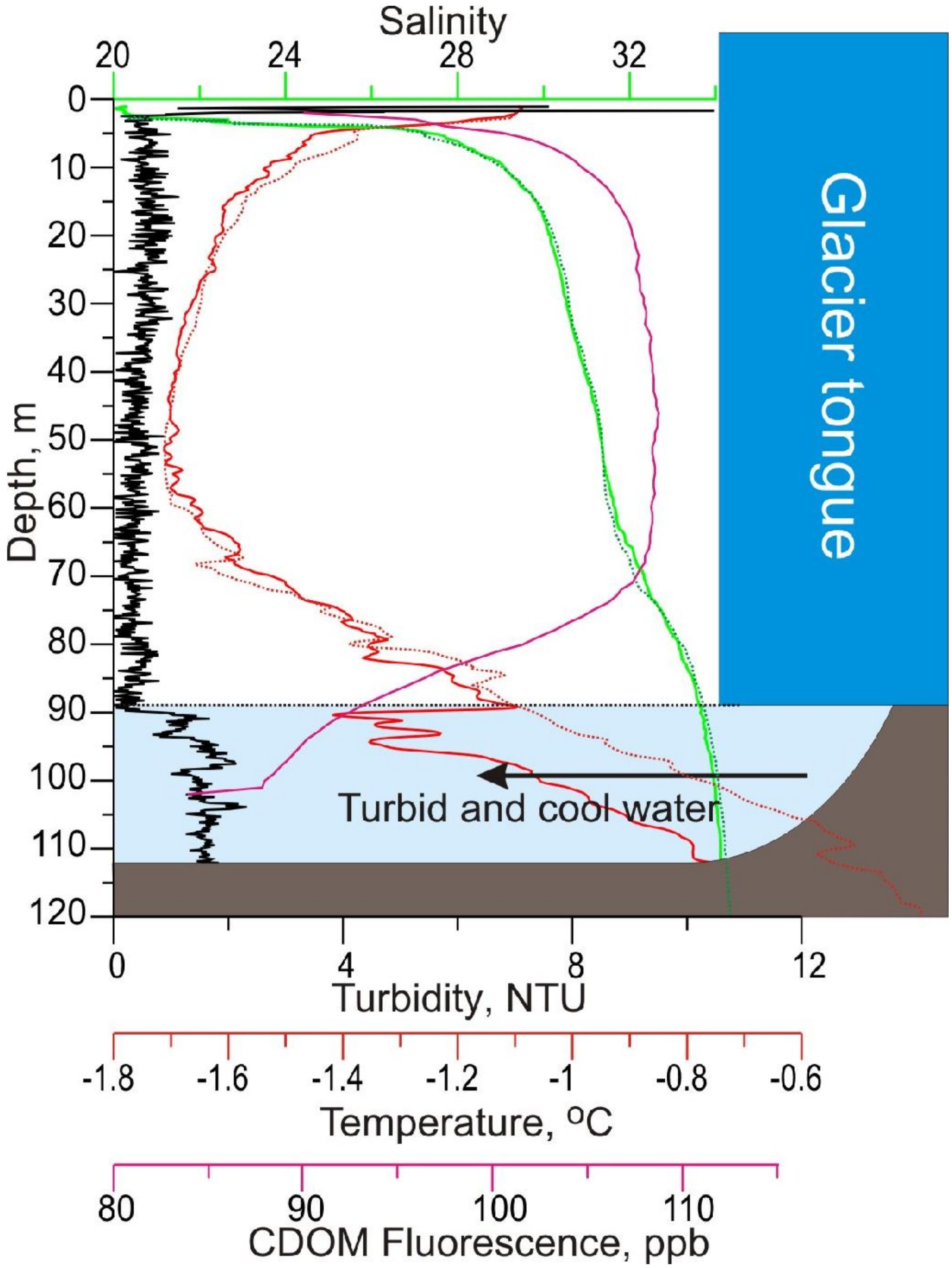


Figure 8: Vertical distribution of temperature (°C, red), salinity (green) and turbidity (NTU, black) at station SN15-13 (Cluster V; solid lines) in front of the tidewater glacier. The CDOM fluorescence (ppb) from the moored I~~P~~TP WETLabs Optical sensor shown for~~ 21 April (dashed violet line) and~~ the 21 April – 11 May mean (solid violet line) for the same location. An ambient profile from SN15-09 (Cluster II; dotted lines) is presented for comparison. The black dotted line at ~90 m depth indicates the suggested depth of the glacier tongue. The glacier tongue is depicted schematically

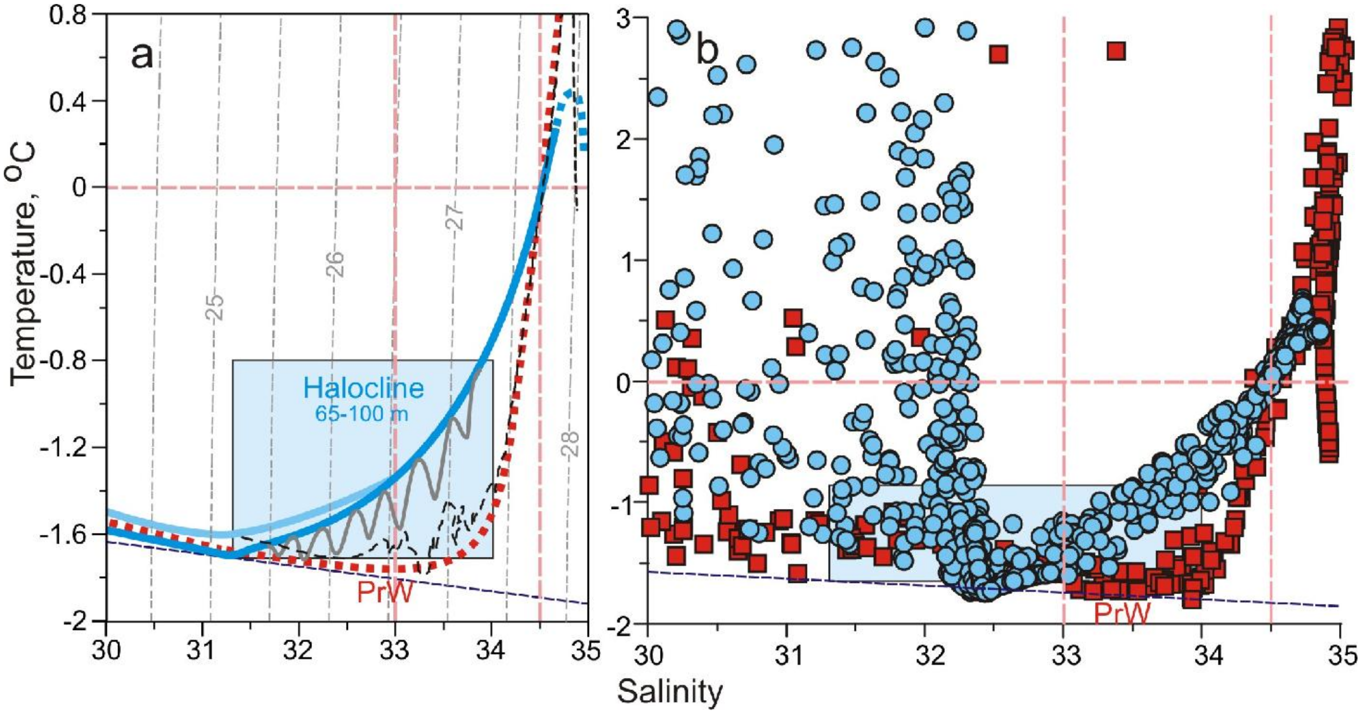


Figure 9: (**a**) Schematic showing formation of the intrusive halocline in clusters III and IV due to interleaving between the PcW (blue curve) and PrW (red dotted curve). Gray curve depicts the intrusive activity. The black dashed curve is station 172 from the Wandel Sea continental slope. The dashed red curve is approximation of the downstream PrW and AW properties at the Greenland continental slope, the NEW area adopted from (**b**). The solid dark/light blue curves are approximations of the PcW and upper AW from Clusters I/II. The dashed blue curve is approximation of the AW properties over the Greenland shelf in the NEW area adopted from (**b**). The gray dashed lines are σ_0 isopycnals in kg m^{-3}. (**b**) Temperature and salinity curves for the CTD stations taken in July-August 1993 between 76.5°N and 81°N and west of 5° W over the NEW area after *Falck* [2001]. Blue circles depict stations from the polynya (shelf) area. Red rectangular depict stations from the Greenland continental slope and Belgica Trough. (**a, b**) Blue shading highlights the approximate properties of the Wandel Sea shelf halocline. The dashed dark blue line is surface freezing temperature.

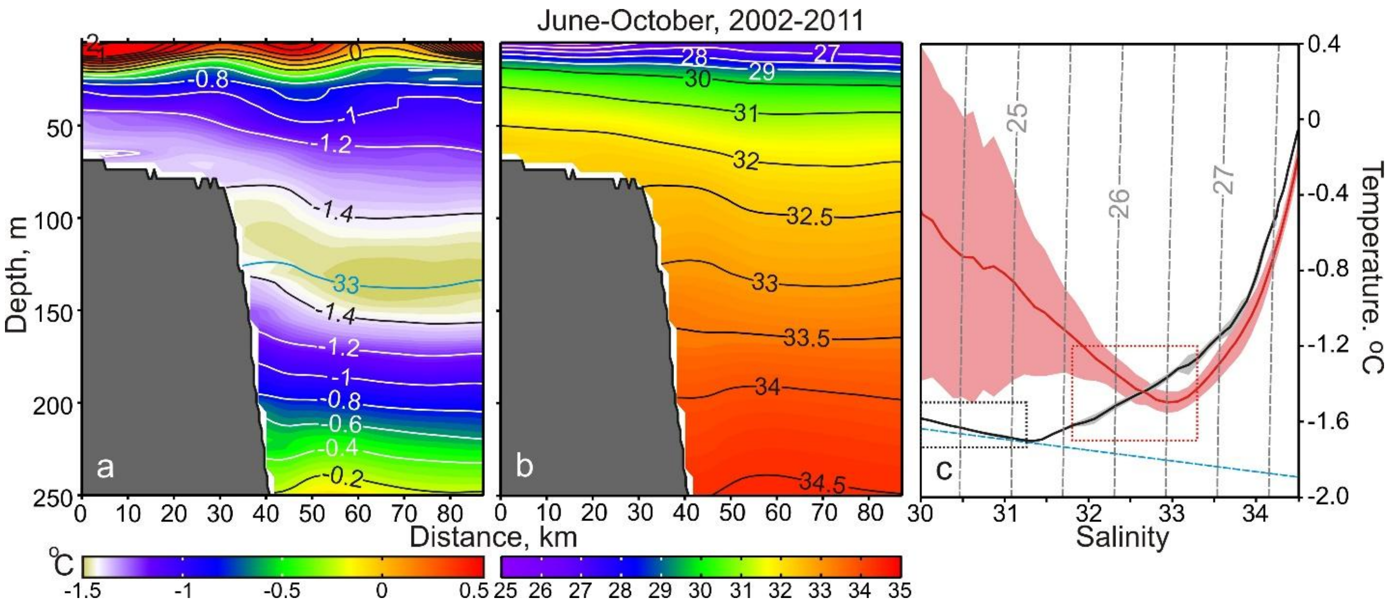


Figure 10: (**a**) Temperature (°C) and (**b**) salinity distributions across the Beaufort Sea continental slope compiled based on 201 ArcticNet CTD profiles occupied between the 225°E and 226°E ~~meridians~~ from June to October 2002-2011 (adopted from *Dmitrenko et al*., 2016). (**c**) In situ mean temperature and salinity curves for the cross-slope Beaufort Sea section (red) and the Wandel Sea shelf CTD profiles from the "basic" Cluster II (black). Shading depicts ±1 standard deviation. The red and black dotted rectangles indicate thermohaline properties of the Halostad over the Beaufort Sea continental slope and Wandel Sea shelf, respectively. The dashed blue line is surface freezing temperature. The gray dashed lines are σ_0 isopycnals in kg m^{-3}.