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Ocean Science Discussions

# 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 CTD profiles taken along the continental slope during the Norwegian FRAM 2014-15 drift. The CTD profiles

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are used to reveal the origin of water masses and interactions with ambient water from the continental slope and the outlet glaciers. 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 glacier front, colder and turbid water intrusions were observed at the base of the Halocline. In temperature-salinity space, these data follow a mixing line that diverges from ambient water properties and indicates 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.

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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 Flade Isblink Ice Cap is located close to Station Nord (Figure 2b). 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].

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, specifically the existence of several submarine glacial troughs, with depths of up to ~180 m, that open to the continental slope (Figure 3). 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 which is partially composed of Pacific-origin water, 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 Atlantic Water outflow through Western Fram Strait 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] –

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Figure 1. The Wandel Sea shelf can also be a source of freshwater that originates from summer snow/sea ice meltwater and from glacier-derived freshwater.

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. They were complemented by CTD profiles taken in June-July 2015 over the Wandel Sea continental slope during the Norwegian FRAM 2014-15 sea ice drift. Our objectives were to investigate the principal features of vertical profiles of salinity and temperature taken over the shelf regions deeper than 100 m.

The paper is structured as follows. Section 2 describes CTD casts, 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 (Figure 3). 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

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(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 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 2a [*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 2) 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

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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).

## 3. Results

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].

Region 1 is located over a submarine glacial trough 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 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). 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

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ambient water from the continental slope. However, lateral exchange still might be possible given the narrow glacial troughs that exist across these shallow shoals [*Nørgaard-Pedersen et al*., 2008].

Region 2 is located over the mid shelf to the north of Station Nord between Prinsesse Thyra and Prinsesse Margreth Islands with depths of 104/112 m (stations STN15-53/54; Figure 3). 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 glacial trough on the inner shelf that extends from the outlet glacier of the Flade Isblink ice cap to the west of Prinsesse Dagmar Island (Figure 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). Region 3 was ice-free during August 2014 (Figure 2) as well as during August 2010-2012 (http://ocean.dmi.dk/arctic/nord.uk.php).

The water column over the Wandel Sea shelf deeper than 100 m shows six distinct layers (Figure 4). The layer immediately below the ice (~1.5–5 m) was relatively fresh (salinity of 16-21; Figure 4) as a result of summer snow/sea ice melt water and freshwater from the glacial runoff. Several stations had extremely fresh surface waters (salinity of 1-12; Figure 4) 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

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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, pers. comm.,* 2016]. The sub-surface halocline layer is characterised by a strong vertical salinity gradient (salinity 1 $m^{-1}$) down to 15 m depth (Figure 4). 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 4) that reached to ~65 m depth (Figure 4). *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 4, 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 4 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 4). 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 4). In 2015, the Halostad and Halocline over the Wandel Sea

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shelf were not observed over the continental slope (Figure 4). Moreover, the thermocline was typically 20-30 m deeper off the shelf (red dashed lines Figure 4), 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 4), 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.

In the following, we focus on the water layer below the sub-surface Halocline, comprised of the Halostad, Halocline, PrW and AW layers (Figures 4-6, Table 1). The 31 CTD profiles with depths greater than 100 m were subdivided into clusters according to their temperature-salinity (*T*-*S*) curves and their variability in *T*-*S* space (Figures 5 and 6 and Table 2). 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 5) we differentiate profiles based on their proximity to the freezing temperature (blue dashed line Figure 5), which indicates how the thermal properties of ambient waters have been modified. (ii) For the salinity range $31.2 < S < 33.5$ (~65-90 m depth; upper Halocline; green shaded area Figures 5 and 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;

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185 2005; *Woodgate et al.*, 2007] and identify shelf-glacier interactions [*Jenkins*, 1999; *Stevens et al.*, 2015]. (iii) For the salinity range > 33.5 (> 90 m depth; low Halocline; pink shaded area; Figures 5 and 6) we use the appearance of thermohaline intrusions and the slope of the mixing line to differentiate the clusters (Figure 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 [e.g., *Gade*, 1979; *Jenkins*, 1999; *Straneo et al.*, 190 2012; *Wilson and Straneo*, 2015].

The intrusions along isohalines suggest isopycnal interleaving (Figures 5b and 6). 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 195 different clusters based on the prescribed salinity range. We also defined a "transit" cluster (Figure 6a) 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). 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.

200 Cluster I is comprised of the nine CTD stations with depths greater than 100 m in Regions 2 and 3 (SN15-31/35/53/54/79-83; Figure 7). 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 (Figures 4 and 5a). For example, all stations from Region 3 exceeded the potential freezing temperature by ~0.1°C, 205 while both stations from Region 2 show a similar regularity, but only exceed the potential freezing

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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 the highest temperature offset from the potential freezing temperature is associated with CTD profiles from Region 3, which was ice-free during the preceding summer (Figure 2) and therefore warmed through solar heating. Region 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; Figure 7) is characterised by smooth *TS* curves slightly affected by intrusive activity (Figure 6), with water near the potential freezing temperature in the Halostad ($S < 31.2$; gray shading in Figure 5). 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 $\sigma_0 = 26$ 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 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; Figure 7) is characterized by temperatures that remain within 1 standard deviation through salinities between 31.2 and 33.5 (green shaded area, Figures 5 and 6a), except for two profiles that deviate from the mean by -0.1÷-0.2°C along the 26.9±0.1 kg m$^{-3}$

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isopycnal. In general, stations from Cluster III occupy almost the same area as Cluster II (Figure 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; Figure 7) profiles display the most significant intrusive activity within the Halocline between salinities of 31.2 and 33.5 (Figures 5 and 6). 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 6a). 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 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; Figure 7) 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 (Figure 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.

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## 4. Discussion

Below we discuss the potential origin and modifications of the water masses in each of the five clusters 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. Interaction 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 (Figure 6). The ambient water from Clusters II-IV exhibits a background mixing line between the Halocline and AW (Figure 5b) 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-

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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 5 and 6). Similar intrusive interleavings at the front of a tidewater glacier were reported by *Jacobs et al*. [1981], *Jenkins* [1998] and *Mayer et al*. [2000].

For station SN15-13, located ~200 m from the termination of the tidewater glacier (Figure 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 water dynamics (3-5 cm/s as a maximum) 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

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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 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 [e.g., *Magorrian and Wells*, 2016].

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 $\Delta S$ that can be estimated from:

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

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. $\Delta T$ 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 5b and 7). We know that the initial salinity then has to be higher than 33.65. Looking at the ambient profiles (Figure 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, $\Delta T$ is 1°C and $\Delta S$ 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:

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$$\alpha \Delta T = \beta \Delta S$$

Here $\alpha$=0.4×10$^{-4}$ $^{o}$K$^{-1}$ is the coefficient for the heat expansion around –1$^{o}$C and $\beta$=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. 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 over the outer shelf (Figure 7) adjacent to the Greenland continental slope, where a water mass with different thermohaline properties is located (Figure 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 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 4). We note, however, that the water mass structure over the continental slope of Northeast Greenland shows significant

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interannual variability [e.g., *Falck et al.,* 2005]. Overall, the distinct difference between the on-shelf and off-shelf water mass structure (Figure 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 5b, 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).

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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

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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 4). 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 $s^{-1}$. The Acoustic Doppler current profiler data from the mooring temporarily deployed at SN15-13 revealed that 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, pers. comm.,* 2016]. 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

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410 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.

415 **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 shallower AW layer recorded over the Wandel Sea shelf and the deeper AW layer found over the continental slope should be attributed to the different branches of the AW outflow from the Arctic 420 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 425 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 430 Summer Water [*Woodgate et al*., 2005] and the Alaskan Coastal Water [*Pickart et al*., 2005]. Below the

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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 4). 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

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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). The glacier melt water provides the low CDOM contribution, which is comparable to background low levels in AW [*Stedmon et al*., 2015]. Overall, this confirms the remote origin of the Halostad layer over the Wandel

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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 4). 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 6a).

## 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

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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

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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 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.

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(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 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.

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## Tables

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

| Water layer | Acronym | Property range (from/to) | | | |
|---|---|---|---|---|---|
| | | Depth, m | Temperature, °C | Salinity | $\sigma_0$, 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 |

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**Table 2**: Description of the Wandel Sea CTD clusters

| Cluster # | Cluster name | Station # | Main features | Property range (from/to) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Depth m | Temp. °C | Salinity | $\sigma_0$ 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 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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 |

**Figure captions**

**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.

**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 black rectangle indicates the 2014 study area shown in Figure 3. Red/yellow/blue dashed rectangles depict regions 1/2/3, respectively, with depth exceeding 100 m.

**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

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720 the multi-year landfast ice (~2 m to > 4 m thick). White and black 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
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**Figure 4**: 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 3b for station position) and on the Wandel Sea upper continental slope (ARKXXIII/2 268; dotted
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**Figure 5:** *In situ* temperature and salinity curves for the CTD stations >100 m depth with $\sigma_0$ 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

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halocline layer of the water column is enlarged in Figure 6a where Clusters II-V are distinguished. In (**a**) and (**b**) 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 (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.

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**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 $\sigma_0$ isopycnals in kg $m^{-3}$.

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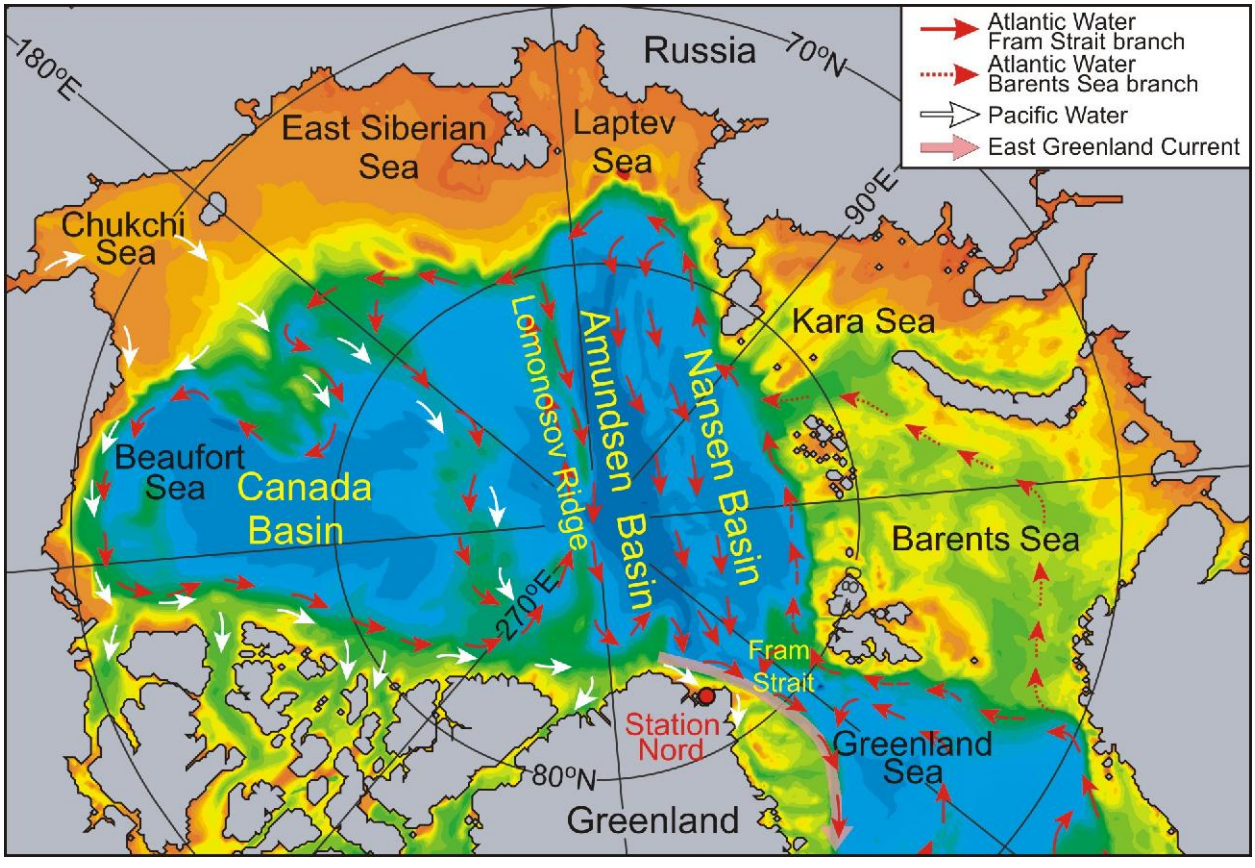


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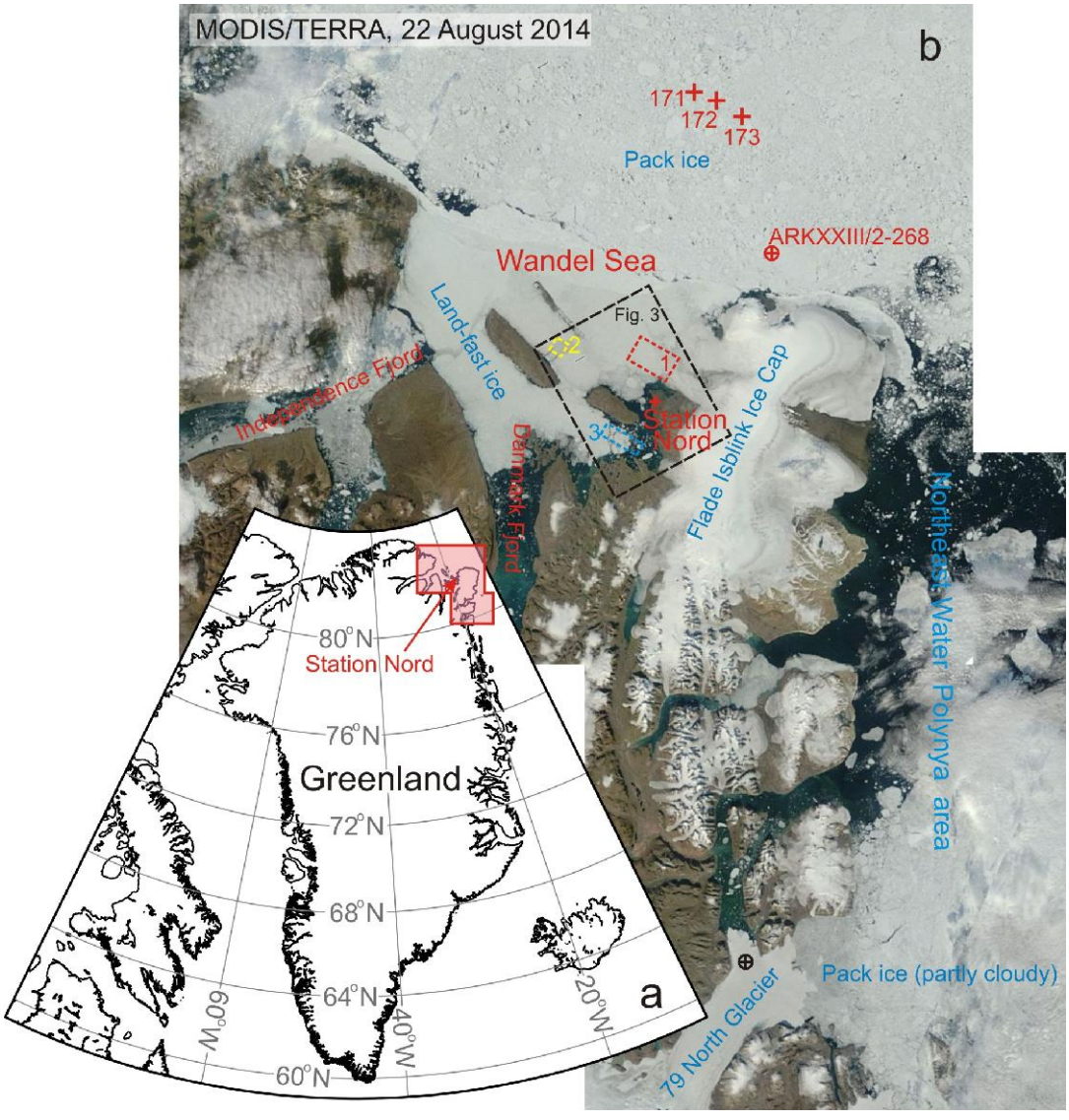


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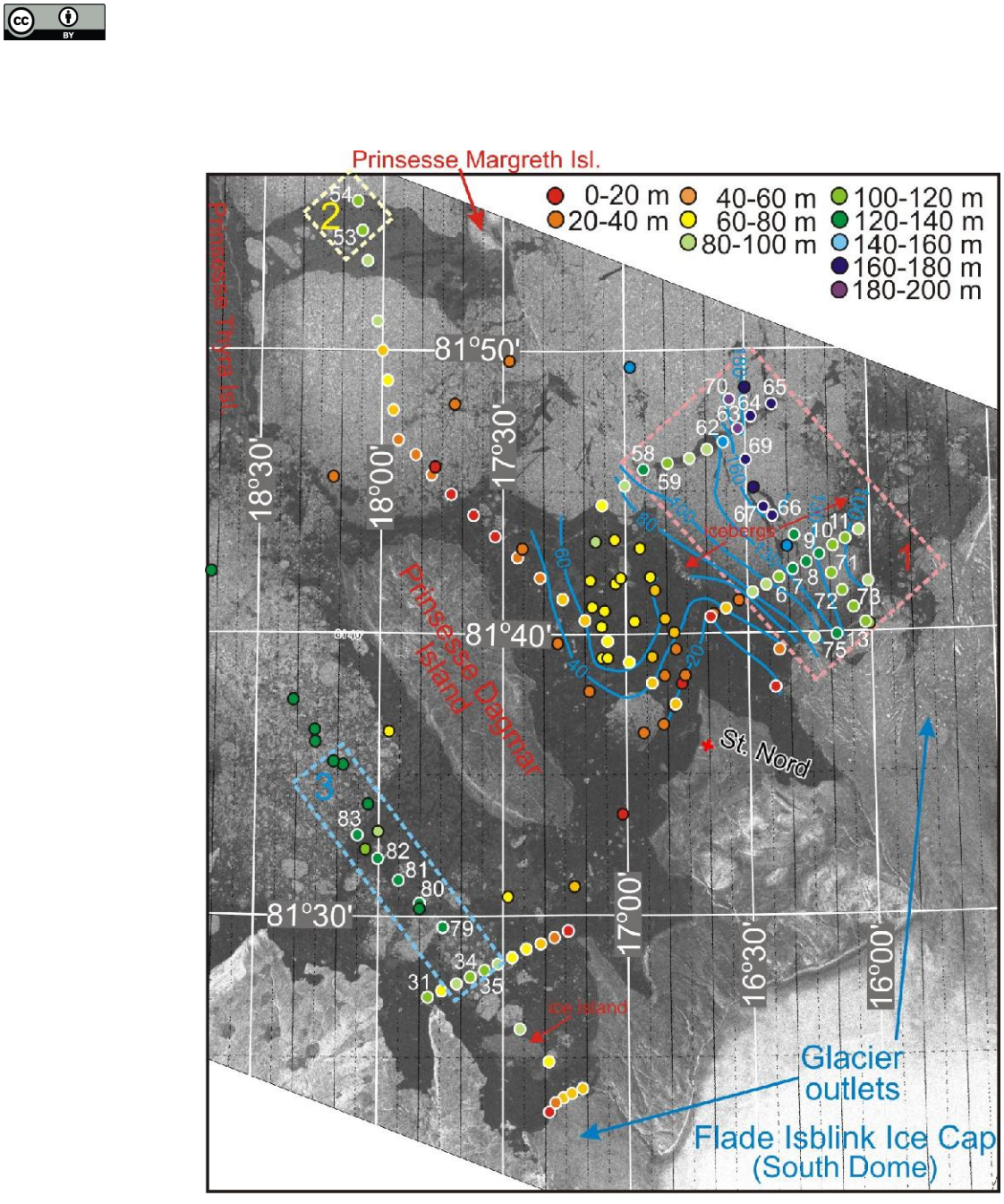


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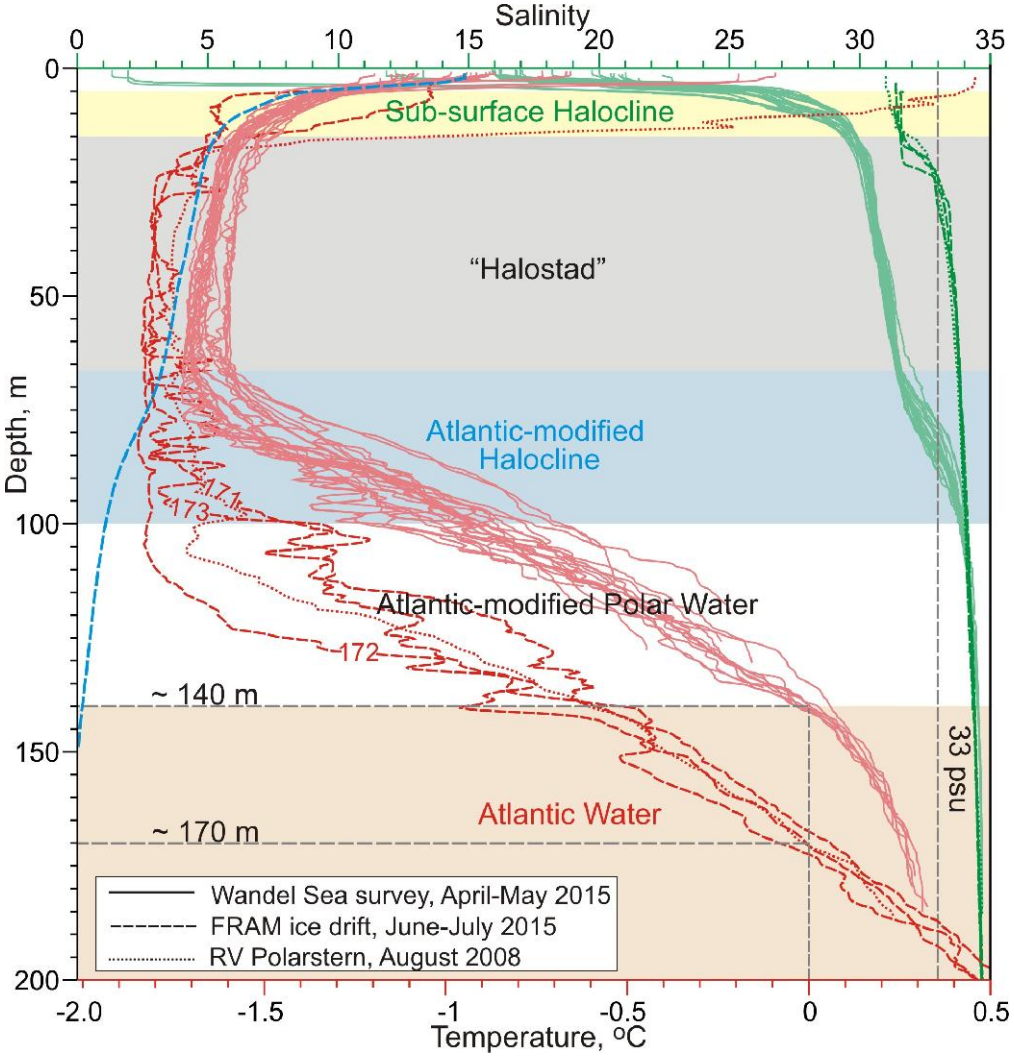


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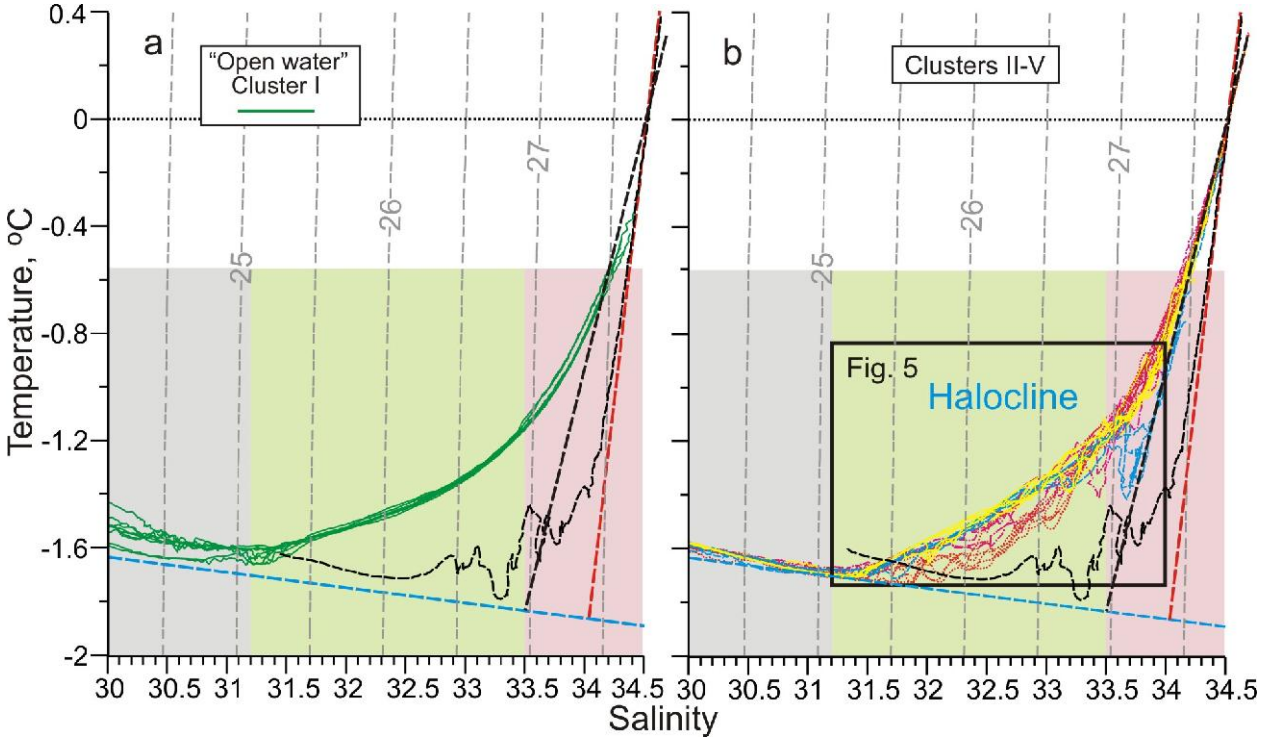


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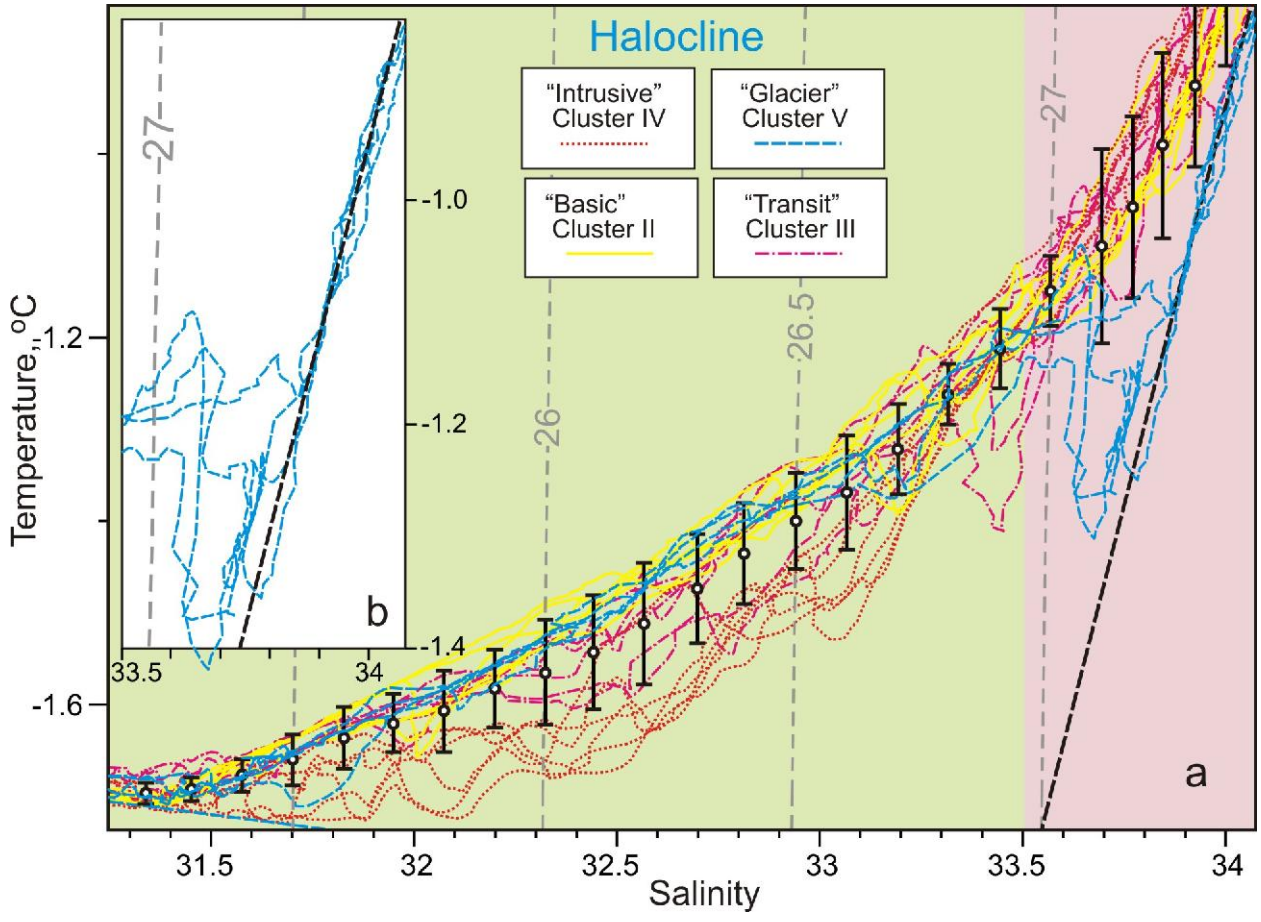


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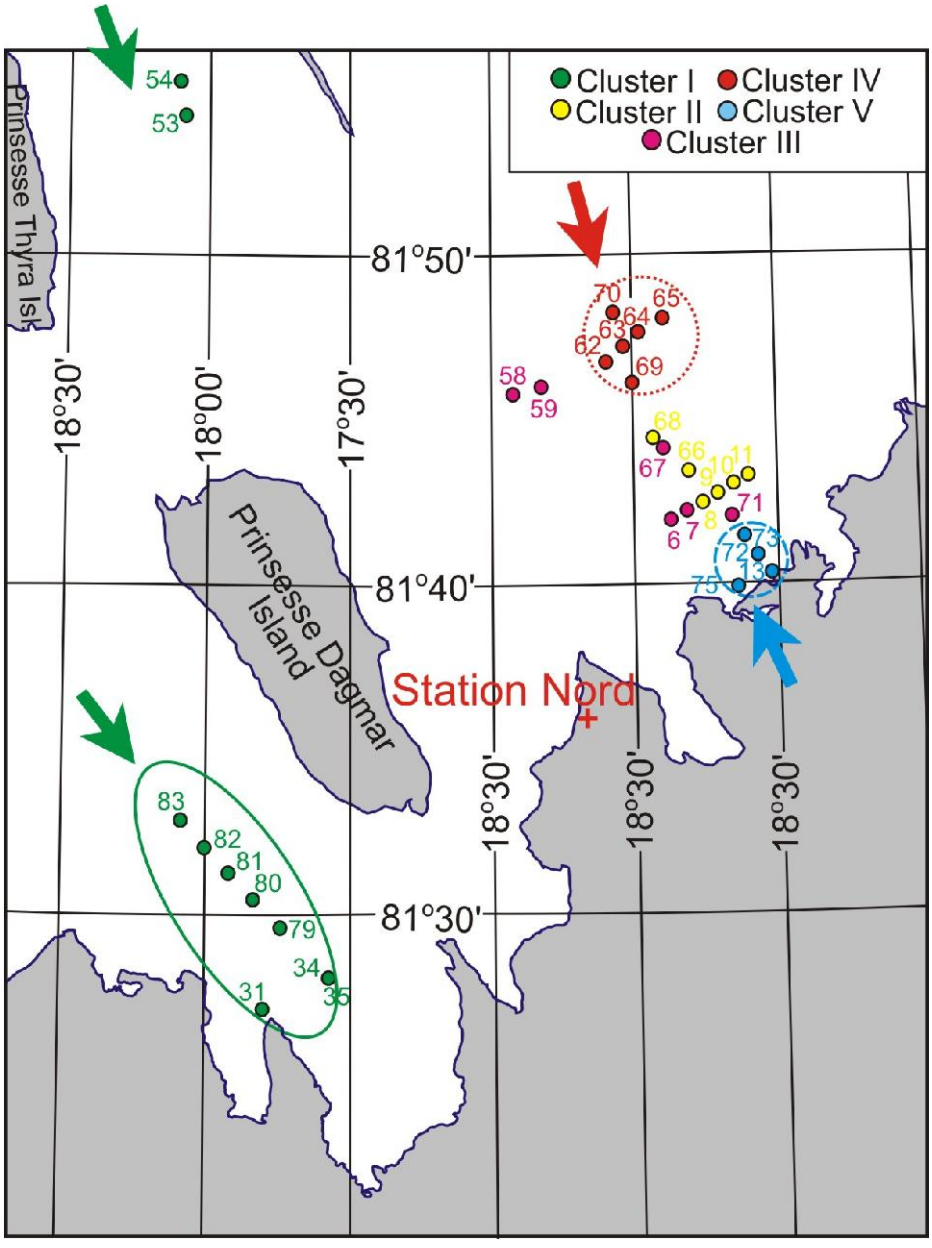


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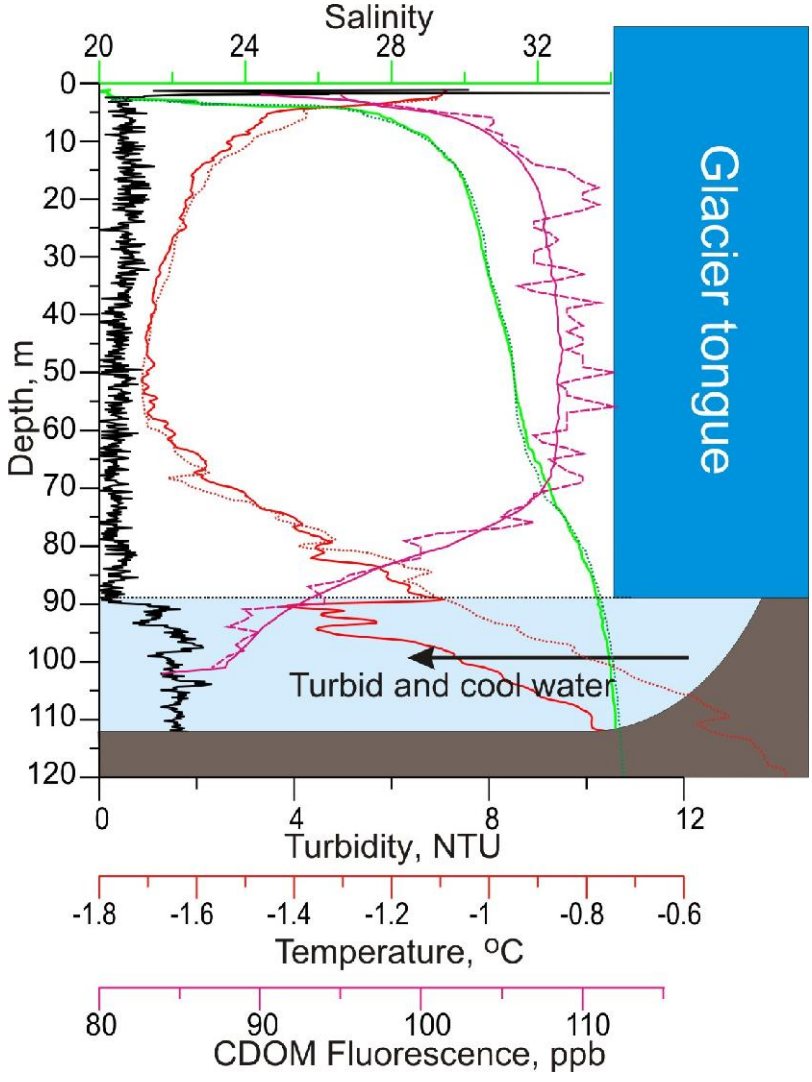


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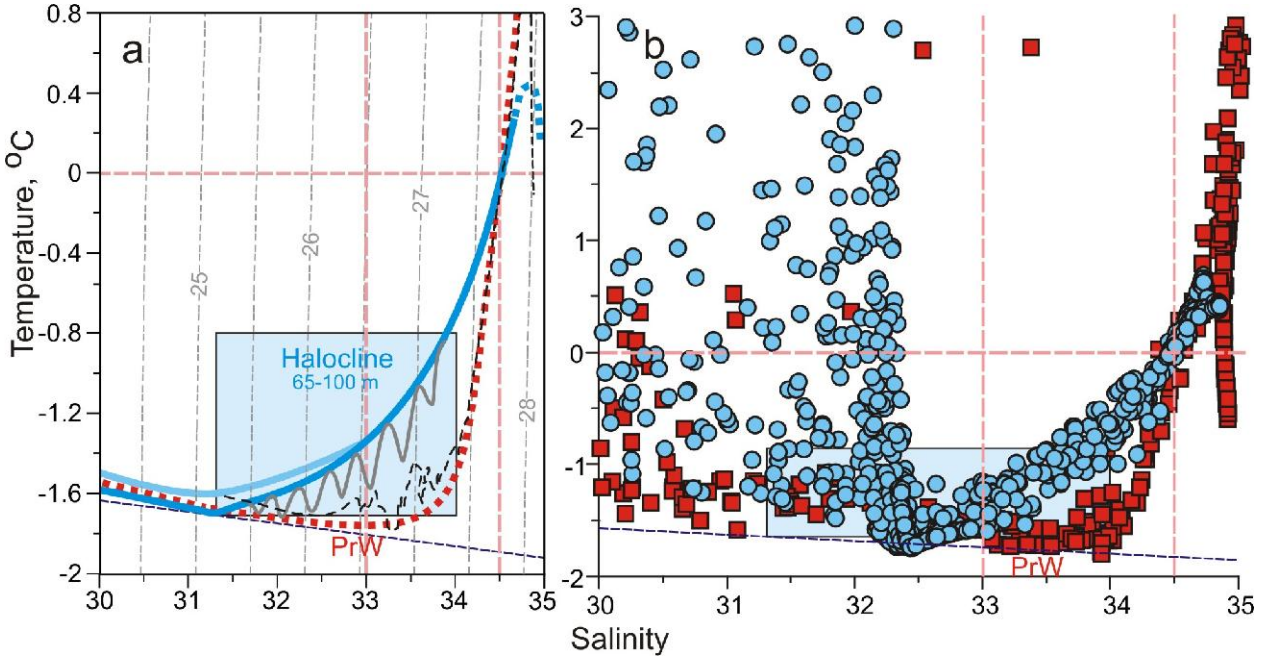


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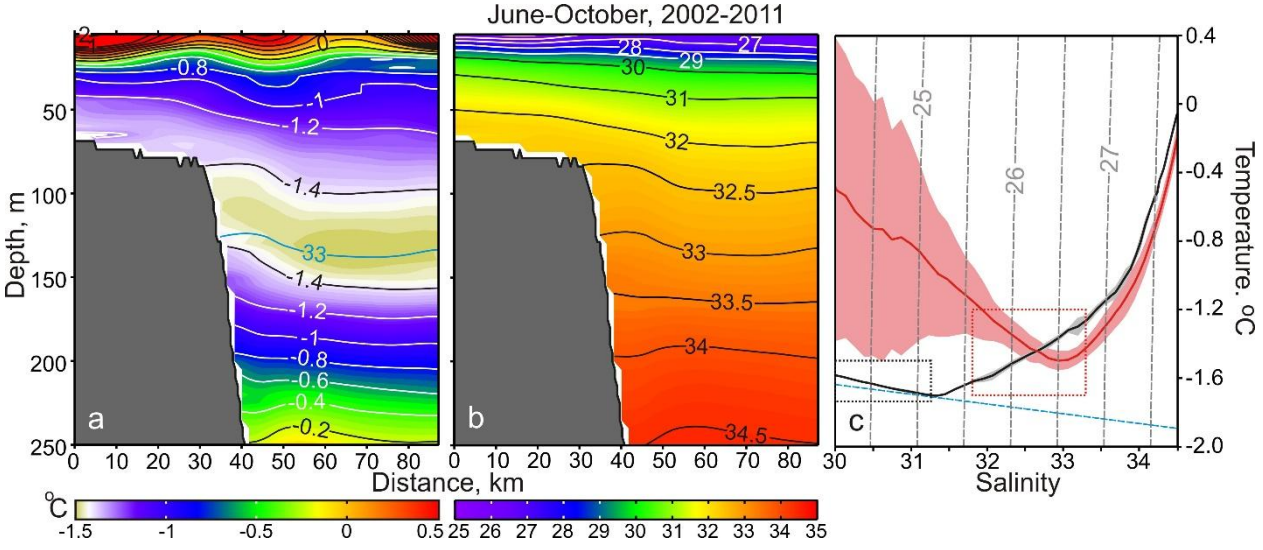


**Figure 10**: (**a**) Temperature (°C) and (**b**) salinity distributions across the Beaufort Sea continental slope compiled based on 201 ArcticNet CTD profiles occupied between the 225°E and 226°E meridians from June to October 2002-2011 (adopted from *Dmitrenko et al*., 2016). (**c**) In situ mean 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 $\sigma_0$ isopycnals in kg $m^{-3}$.