1	Arctic Ocean outflow and glacier-ocean interaction modify water over the Wandel Sea shelf	1
2	(Northeast Greenland)	
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Abstract: The first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf in 23 North Eastern Greenland were collected in April-May 2015. They were complemented by CTDs taken 24 25 along the continental slope during the Norwegian FRAM 2014-15 drift. The CTD profiles are used to 26 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 27 Ocean. The underlying Halocline separates the Pacific Water from a deeper layer of Polar Water that has 28 interacted with the warm Atlantic water outflow through Fram Strait recorded below 140 m. Over the outer 29 30 shelf, the Halocline shows numerous cold density-compensated intrusions indicating lateral interaction with 31 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 32 33 these stations indicate a mixing line that is different from the ambient water and seems to be conditioned by 34 the ocean-glacier interaction. Our observations of Pacific Water are set within the context of upstream 35 observations in the Beaufort Sea and downstream observations from the Northeast Water Polynya, and 36 clearly show the modification of Pacific water during its advection across the Arctic Ocean. Moreover, 37 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 38 Fram Strait. 39

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# 41 **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 northeastern 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.

53 The Wandel Sea is predominantly covered by landfast multiyear sea ice all year around, and only 54 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<sup>2</sup> 55 and maximum thickness of 600 m that overlies bedrock that is on average 100 m below sea level [e.g., 56 57 Palmer et al., 2010; Rinne et al., 2011]. In general, the Wandel Sea is rather a glacial inlet than a shelf sea. 58 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. 59 60 The bathymetry of the Wandel Sea shelf and upper continental slope is poorly known. Nørgaard-Pedersen et al. [2008] provided limited information on the bottom topography in the area surrounding Station Nord, 61 specifically the existence of several submarine glacial troughs, with depths of up to ~180 m, that open to 62 63 the continental slope (Figure 4a). 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 64 65 the Wandel Sea shelf. From very general considerations, the Wandel Sea shelf is expected to be under the 66 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 67 68 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 69 70 freshwater budget that links the Arctic Ocean to the global climate system [e.g., de Steur et al., 2009]. The 71 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.

77 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 78 Ocean conditioned by its inflow through eastern Fram Strait and Barents Sea [e.g., Rudels et al., 1994; 79 Rudels, 2012] – Figure 1. The interaction of warm Atlantic Water with tidewater glacier outlets along the 80 southeast coast of Greenland results in ocean-driven glacier melting. This generates additional fresh water 81 82 flux contributing to the regional fresh water budget [e.g., Straneo et al., 2011, 2012; Sutherland and 83 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. 84

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 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" 97 CTD cluster from the Wandel Sea outer shelf. Sections 4.3/4.4 discuss local/remote origins of the Wandel
98 Sea water masses. Finally, section 5 concludes the analysis and discusses limitations.

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## 100 **2. Data and methods**

Between 17 April and 15 May 2015, 86 CTD profiles (labelled SN15 - XX; XX is the station 101 number) were collected from the landfast sea ice (1.0 to 3.5 m thick) on the Wandel Sea shelf in Northeast 102 103 Greenland (Figures3 and 4). The CTD observations were carried out with a SBE-19plus CTD that was calibrated prior to the expedition, and was accurate to  $\pm 0.005$  °C and  $\pm 0.0005$  S/m. The CTD was outfitted 104 with a Seapoint Turbidity Meter that measured turbidity in nephelometric turbidity units (NTU). 105 Additionally we used vertical profiles of the colored dissolved organic matter (CDOM) from an Ice 106 107 Tethered Profiler (ITP) by McLane Research Laboratory that was temporarily deployed at SN15-13 from 21 April to 11 May (Figure 4b). The ITP collected a profile every 2 hours between 3 m and 101 m depth, 108 109 and was equipped with a Wetlabs ECO sensor for measuring backscatter intensity, Chlorophyll 110 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 111 112 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 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 [*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 seaice, 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 collected in waters deeper than 100 m (Figure 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].

136 The primary region with depth exceeding 100 m is located over a submarine glacial trough to the 137 north-northeast of Station Nord that ranges in depth from 110-130 m at the tidewater glacier outlet 138 (STN15-13 and 75) to 183 m further off-shore along the trough (STN15-63; Figure 4). The glacial trough 139 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 multivear sea ice (~3.5 m thick; lighter colours in 140 141 Figure 3). Several CTD stations were performed through refrozen leads that contained younger and 142 therefore thinner sea ice (~1.5 m thick; darker colours in Figure 3). The glacial trough was paralleled on 143 both sides by numerous icebergs that appeared to be grounded on the marginal lateral moraine which can 144 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 is located to the northwest of Station Nord between Prinsesse Thyra and Prinsesse Margreth Islands with depths of 104/112 m (stations STN15-53/54; Figure 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.

153 The glacial trough to the west-southwest of Station Nord from the glacial outlet of the Flade Isblink 154 ice cap to the west of Prinsesse Dagmar Island also exceeds 100 m depth (Figure 4a). During our field work 155 the glacier was grounded at  $\sim$ 35-40 m depth. The trough extending from this outlet glacier quickly reached 156 depths of ~100 m (STN15-35) and reached a maximum depth of 127 m (STN15-79). During the field 157 campaign this region was covered with a mix of first year (~1.2 m thick) and multiyear sea ice (~3 m 158 thick), with icebergs and an ice island frozen within the fast ice (Figure 3) that corresponds to the typical ice conditions over this area. During August 2014 (Figure 2) as well as during August 2010-2012 this 159 region was ice-free (http://ocean.dmi.dk/arctic/nord.uk.php). 160

- 161
- 162 **3. Results**

## 163 **3.1. Water mass structure**

The water column over the Wandel Sea shelf shows six distinct layers (Figure 5). The layer immediately below the ice (~1.5–5 m) was relatively fresh (salinity of 16-21; Figure 5) 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 5) 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 [*Bendtsen et al.*, 2017]. The sub-surface halocline
layer is characterised by a strong vertical salinity gradient (salinity 1 m<sup>-1</sup>) down to 15 m depth (Figure 5).
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 5) that reached to
~65 m depth (Figure 5). *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 5, Table
1).

Below the Halostad (below 75 m depth), temperatures increased steadily through the Halocline 177 (with salinity centered around 33) and Atlantic modified Polar Water (PrW) – Figure 5 and Table 1. The 178 Halocline is further distinguished from the Halostad and PrW by its high vertical salinity gradient of 0.07 179 180 m<sup>-1</sup> (Figure 5). 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). 181 Atlantic modification of the Halocline is evident from the increase in temperature through the Halocline. 182 Furthermore, the Halocline shows intrusions of cooler water, which is further described and discussed for 183 tracing the shelf-slope and ocean-glacier interactions, as well as the Pacific Water (PcW) and AW outflow 184 185 from the Arctic Ocean through western Fram Strait.

Comparing CTD profiles collected over the Wandel Sea shelf (solid lines) and those collected off-186 shelf (dashed lines) reveals substantial differences in the temperature profiles down to 180 m, and in the 187 salinity profiles down to 110 m (Figure 5). In 2015, the Halostad and Halocline over the Wandel Sea shelf 188 were not observed over the continental slope (Figure 5). Moreover, the thermocline was typically 20-30 m 189 190 deeper off the shelf (red dashed lines Figure 5), specifically the upper boundary of the AW was found at 191 170 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 5), which reveals little variability in the water mass structure between 192 193 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

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## 199 **3.2. CTD clustering**

# 200 3.2.1. Methods of CTD clustering

In the following, we focus on the water layer below the sub-surface Halocline, comprised of the 201 Halostad, Halocline, PrW and AW layers (Figures 5-7, Table 1). The 31 CTD profiles with depths greater 202 203 than 100 m were subdivided into clusters according to their temperature-salinity (TS) curves and their 204 variability in the TS space (Figures 4b, 6 and 7 and Table 2). The clustering was conducted to assess the 205 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 206 207 Figure 6) we differentiate profiles based on their proximity to the freezing temperature (blue dashed line Figure 6), which indicates how the water thermal properties have been modified. (ii) For the salinity range 208 31.2 < S < 33.5 (~65-90 m depth; upper Halocline; green shaded area Figures 6 and 7) we differentiate 209 210 clusters based on the appearance of distinctive thermohaline intrusions within the TS curves. These 211 intrusions increase the TS variability and disrupt the initially smooth TS curves, which indicate interaction 212 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., 213 214 2007] and identify shelf-glacier interactions [Jenkins, 1999; Stevens et al., 2016]. (iii) For the salinity range > 33.5 (> 90 m depth; low Halocline; pink shaded area; Figures 6 and 7) we use the appearance of 215 216 thermohaline intrusions and the slope of the mixing line to differentiate the clusters (Figures 7d and 7e). The displacement of the mixing line indicates the thermodynamic "meltwater" end member [e.g., Jenkins, 217 218 1999; Straneo et al., 2012; Wilson and Straneo, 2015].

The intrusions along isohalines suggest isopycnal interleaving occurs within the area (Figures 6b and 7c). 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<sup>-3</sup> interval of the potential density. All TS curves exceeding  $\pm 1$  standard deviation at more than 50% of the 0.1 kg m<sup>-3</sup> intervals were added to the different clusters based on the prescribed salinity range. We also defined a "transit" cluster (Figure 7b) showing weak thermohaline intrusions below one standard deviation of the mean.

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

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## 228 **3.2.2.** *Description of clusters*

Here we assess the main patterns of clusters putting them in the context of their geographical location on the Wandel Sea shelf and the sea-ice features.

231 Cluster I is comprised of the nine CTD stations occupied (i) along the glacial trough to the west-232 southwest of Station Nord and (ii) between Prinsesse Thyra and Prinsesse Margreth Islands (SN15-233 31/35/53/54/79-83; Figures 4b and 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 234 235 underlying water column (S > 31.2) that appear to be unaffected by intrusive activity (Figure 6a). The 236 highest temperature offset from the potential freezing temperature is associated with CTD profiles from the 237 glacial trough, which was ice-free during the preceding summer (Figure 2b) and therefore warmed through 238 solar heating. Region between islands 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 239 240 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 7a), with water near the potential freezing temperature in the Halostad (S < 31.2; gray shading in Figure 6b). Stations from this cluster occupy 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 and 7b), except for two profiles that deviate from the mean by -0.1 to -0.2°C along the  $26.9\pm0.1$  kg m<sup>-3</sup> isopycnal. In general, stations from Cluster III occupy almost the same area as Cluster II (Figure 4b) 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 253 significant intrusive activity within the Halocline between salinities of 31.2 and 33.5 (Figures 6b and 7c). 254 Within this range all TS curves show negative temperature anomalies greater than one standard deviation 255 for at least half of the 0.1 kg m<sup>-3</sup> intervals (Figure 7c). In contrast, the profiles from this cluster have 256 positive temperature anomalies of about one standard deviation throughout the underlying water where S >257 258 33.5. Profiles from this cluster were taken over the compact area on the eastern flank of the glacial trough 259 on the Wandel Sea outer shelf (Figure 4b) and are the closest profiles to the continental slope. Hereafter we refer to these stations as the "intrusive" cluster. 260

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). 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 268 distinct mixing line that is shifted towards lower temperatures relative to the ambient profiles. Profiles
269 from this cluster were collected near the front of the glacial tongue, thus we refer to this cluster as the
270 "glacier" cluster.

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# 272 **4. Discussion**

Below we discuss the potential origin and modifications of the water masses in 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).

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# 278 4.1. Shelf water interaction with tidewater glacier

We speculate that cluster V shows features that we attribute to the ocean-glacier interaction. These 279 are (i) the abnormal intrusive activity at the base of the Halocline and (ii) the transition of profiles in the TS 280 281 space towards a new mixing line for the underlying Atlantic modified PrW at the glacier front (Figures 7d and 7e). The ambient water from Clusters II-IV exhibits a background mixing line between the Halocline 282 and AW (Figure 6b) which seems to be unaffected by the ocean-glacier interaction. During summer, 283 284 significant surface glacial runoff provides a new end-member to this mixture. However, during winter there 285 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 286 glacial melt water is negligible during winter, the glacier can still modify the ambient mixing line through 287 288 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 293 294 ambient PrW modified by interaction with the underlying warm AW. The sub-glacier freshwater discharge 295 can also reduce the salinity of this water mass; however, the sub-glacier discharge is likely negligible 296 during winter. For the floating glacier, a lateral interaction between the water below the glacier tongue and 297 the Atlantic-modified PrW can (i) give rise to the intrusions we observed at the base of the Halocline layer 298 and (ii) modify the background mixing line towards colder temperatures as also observed (Figures 6b and 299 7d). Similar intrusive interleavings at the front of a tidewater glacier were reported by Jenkins [1999], 300 Mayer et al. [2000] and Stevens et al. [2016].

For station SN15-13, located ~200 m from the termination of the tidewater glacier (Figure 4b), the 301 302 CTD profile shows an intrusion of cool, turbid water between 88 and 97 m depths that caused a temperature 303 inversion of -0.32°C and a sharp increase in the water turbidity from 0.2 to 1.5 NTU (Figure 8). A similar 304 rapid increase in turbidity with depth was also recorded at the Helheim Glacier in southeast Greenland 305 [Straneo et al., 2011]. We attribute this increase to the lower boundary of the glacier tongue at 88 m depth. 306 In this case the turbid water can be attributed to subglacial discharge, or submarine melting of ice releasing sediments. The currents (3-5 cm/s as a maximum, Kirillov et al., 2017) are too weak for resuspending the 307 308 20 m thick bottom layer. Assuming the ratio of glacier/water densities to be 0.917, we get a glacier 309 elevation above the sea surface of  $\sim$ 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  $0.28^{\circ}$ 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 317 318 saline water are observed around 90 m depth, which is the estimated lower boundary of the floating ice 319 tongue. The water circulating below the glacier is initially warmer than the *in situ* freezing point of 320 seawater and will be cooled as it gets in contact with the bottom of the glacier. The lost heat is partly used 321 to melt ice and partly conducted into the glacier, increasing its temperature. Here we assume that the largest 322 part of the heat goes to melting and we presently ignore the fraction of heat conducted into the glacier. We 323 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 324 larger than the density increase due to cooling, and the less saline water will ascend along the lower 325 326 boundary of the glacier, until it terminus. At this point the water will penetrate into the ambient water 327 column at its density level few meters above the depth that the meltwater was released, forming colder, less 328 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  $\Delta S$  that can be estimated from:

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

Here  $c_p = 3980 \text{ J}^{\circ}\text{C}^{-1}\text{kg}^{-1}$  is the heat capacity of sea-water and  $L = 334500 \text{ Jkg}^{-1}$  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  $\Delta T \sim 0.3^{\circ}$ C (Figures 4b and 6b). We know that the initial salinity then has to be higher than 33.65. Looking at the ambient profiles (Figure 5) 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  $-1.4^{\circ}C$  (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:

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

Here  $\alpha = 0.4 \times 10^{-4} \text{ °K}^{-1}$  is the coefficient for the heat expansion around  $-1^{\circ}\text{C}$  and  $\beta = 8 \times 10^{-4} \text{ psu}^{-1}$  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.

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# 4.2. Shelf water 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 (Figure 4b) adjacent to the Greenland continental slope, where a water mass with different thermohaline properties is located (Figure 5). 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). 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). 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) 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.

377 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. 378 379 2001], which is downstream from the Wandel Sea shelf (Figures 1 and 2b). The TS curves from the NEW 380 area show two distinct modes: (i) the polynya (shelf) mode, which is similar to the "basic" Cluster II 381 derived for the Wandel Sea shelf (Figure 4b, 7a and dark blue lines in Figure 9a) except for a slightly 382 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 383 384 curve (red lines in Figure 9a). Specifically the TS line of the continental slope mode extends linearly 385 through the Halostad to salinity of  $\sim 34$  (red dashed line in Figure 9a; red rectangles in Figure 9b). 386 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 389 390 79N glacier outlet (Figure 2b), Straneo et al. [2012] used the upper continental slope CTDs as ambient 391 stations and compared them to CTD profiles taken through a rift in the floating glacier tongue (see Figure 392 2b for the glacier station position). For the water layer at ~40-90 m depth, they reported ambient water that 393 was saltier than water below the glacier tongue by  $\sim$ 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 394 395 between the shelf Halostad/Halocline and the continental slope PrW (Figure 9). Thus, freshening reported 396 by Straneo et al. [2012] could be alternatively explained by the occurrence of the Halostad-like freshened 397 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.

#### 402 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 5). 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 414 415 Ocean [e.g., Dmitrenko et al., 2010]. Dmitrenko et al. [2012] showed that significant velocity shear over 416 the Laptev Sea shelf, attributed to the lunar semiduirnal baroclinic internal tide M2 with velocity ~15 cm/s 417 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<sup>-1</sup>, and the most 418 energetic M2 tidal currents are weak, decreasing from ~2 cm/s beneath the ice to ~1 cm/s below 60 m depth 419 420 [Kirillov et al., 2017]. Moreover, the multiyear landfast ice cover over the Wandel Sea shelf precludes the wind stress from vertically mixing the stratified water column. 421

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  $\sim$ 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.

429

## 430 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<sup>-3</sup> [*Rudels et al.*, 2002]

that are comprised of the river runoff and net precipitation water, but also of the less saline PcW that 439 440 enters the Arctic Ocean through Bering Strait [Jones et al., 1998, 2003, 2008; Rudels et al., 2002; Falck et 441 al., 2005; de Steur et al., 2009; Sutherland et al., 2009] - Figure 1. PcW within the Arctic Ocean is 442 generally assigned to water with  $S \leq 33$  [von Appen and Pickart, 2012] and has both a summer and winter 443 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] 444 445 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 446 447 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 ~ - $1.7^{\circ}$ 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 5). 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 464 465 Halostad in the Wandel Sea and Canada Basin suggests that significant modifications occurred during 466 transit of the winter PcW from the Bering and Chukchi Seas to the Wandel Sea. It seems that the winter 467 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, 468 the PcW fraction is comparable with the river water fraction. Moreover, water from the Siberian shelves, 469 470 especially the Laptev Sea shelf also has the same salinity and temperature range [e.g., Dmitrenko et al., 471 2011] and can mix into and cool the summer PcW advected with the Transpolar Drift to the NE Greenland 472 coast. This assumes that the river water impacts a Wandel Sea Halostad initially comprised of the winter PcW. 473

474 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 475 476 tracer of the Arctic Ocean terrigenous organic matter primarily attributed to the Eurasian and American 477 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 SN15-13 478 is consistent with results from the Canada Basin where this maxima is attributed to the winter PcW [e.g., 479 480 Guéguen et al., 2007] and the continental river runoff water [e.g., Granskog et al., 2012]. For the 481 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 482 483 remote origin of the Halostad layer over the Wandel Sea shelf and strengthens our discussion on the 484 modification of the Pacific-derived Halostad by river runoff while en route from the Canada Basin to Fram 485 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 5). 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<sup>-3</sup> 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 7c).

499

## 500 5. Summary and conclusions

501 The first-ever CTD observations over the Wandel Sea shelf and continental slope were collected in 502 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 503 glaciers entering the Wandel Sea. The stations taken on the Wandel Sea shelf and farther to the east on the 504 505 Greenland slope reveal two pathways for the advected water masses, one over the shelf and one along the 506 continental slope. The one over the slope has warm, saline AW lying below a deep, cold, less saline and 507 fairly homogenous upper layer that is capped by low salinity surface water created by seasonal ice melt and 508 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 509 510 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, 521 522 seems to be either missing or only occupying a narrow depth range. Instead the coldest water is found in 523 the Halostad with salinity around 31 instead of 33. The low salinity upper layer and the thick ice cover in 524 winter preclude the local homogenization of the water column down to the Halostad. Thus, the Halostad 525 must be advected from elsewhere. A conceivable scenario could be that most of the PcW drains out of the 526 Arctic Ocean through the Canadian Arctic Archipelago. This likely makes the AW ascend and it would 527 allow water from the Polar Mixed Layer, of Atlantic or Pacific origin, circulating in the Beaufort Gyre and 528 in the Arctic basins to replace the water leaving through the straits in the archipelago and penetrate onto the shelf, creating a different upper laver above the AW. 529

530 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.

537 (ii) The Halocline layer centered at ~80 m (salinity of ~33) separates the Pacific-origin cold
538 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 ( $T \sim 0^{\circ}$ 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 550 551 advecting Pacific Water of Arctic origin southward along the northeast Greenland coast. This is consistent 552 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 553 simulations [Hu and Myers, 2013; Aksenov et al., 2016]. Finally, we note that our observations were not 554 555 accompanied by water sampling for determining the nitrate/phosphate relationship commonly used to trace 556 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 557 558 analysis.

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560 Acknowledgments: This study was funded by the Canada Excellence Research Chair program (SR), the 561 Canada Research Chair program (DB), the Canada Foundation of Innovation, the National Sciences and 562 Engineering Research Council of Canada (grant RGPIN-2014-03606, ID), the Manitoba Research and 563 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 564 565 Lennert and Egon Frandsen for technical assistance in the field. We also appreciate outstanding logistical 566 support from the Station Nord Danish military personnel. Dr. John Mortensen (Greenland Climate 567 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 568 Nørgaard-Pedersen kindly provided bathymetric data used in Figure 4a. This work is a contribution to the 569 570 Arctic Science Partnership (ASP) and the ArcticNet Networks of Centres of Excellence programs. For the 571 Wandel Sea CTD data contact ID at igor.dmitrenko@umanitoba.ca.

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# 720 Tables

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

Water layer	Acronym	Property range				
		Depth, m	Temperature, °C	Salinity	$\sigma_{0,}$ kg m <sup>-3</sup>	
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	-	$\sim 65 \div 100$ $\sim -1.75 \div -0.65$		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	er Cluster name	Station #	Main features	Property range			
#				Depth	Temp.	Salinity	$\sigma_0$
				m	°C		kg m <sup>-3</sup>
Ι	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	acier 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

## 726 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. The blue dot roughly identifies location where CTD profiles were collected in the Beaufort Sea.

733 Figure 2: (a) Station Nord (SN) on the Greenland map. The pink shading highlights the Wandel Sea region 734 with adjoining fjord system, Flade Isblink Ice Cap (FIIC), the Northeast Water Polynya (NEW) area and 735 the 79 North Glacier outlet enlarged in panel (b). (b) The MODIS/TERRA satellite image from 22 August 736 2014 taken over the SN/FIIC/NEW area. Red and black circled crosses indicate the CTD stations occupied 737 over the Wandel Sea outer-shelf during the ARKXXIII/2 expedition in August 2008 and in a rift in the 79 738 North Glacier in August 2009. Red crosses depict the CTD stations occupied in June-July 2015 over the 739 Wandel Sea continental slope (> 1000 m depth) during the Norwegian FRAM 2014-15 sea ice drift. The 740 dashed blue rectangle indicates the 2015 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 ( $\sim$ 2 m to > 4 m thick). Yellow circles identify stations with CTD measurements Blue arrows indicate the northern outlet glaciers of the Flade Isblink Ice Cap.

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.

Figure 5: Vertical distribution of temperature (red) and salinity (green) profiles over the Wandel Sea 749 750 shelf ( $\geq$  100 m depth; solid curves) from April and May 2015, over the continental slope (stations 171-173; 751 dashed curves) from June and July 2015 from the Norwegian FRAM 2014-15 ice drift (see Figure 2b for 752 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 753 754 salinity and temperature, respectively, for station STN15-68. The blue dashed curve is the in situ 755 temperature of freezing computed using the mean SN salinity profile (not shown). The vertical dashed line depicts salinity of 33 that separates the PcW and AW in the western Beaufort Sea [von Appen and Pickart, 756 757 2012].

758 **Figure 6:** In situ temperature and salinity curves for the CTD stations >100 m depth with  $\sigma_0$  isopycnals presented (dashed grey lines; kg m<sup>-3</sup>). (a) CTD profiles grouped into Cluster I "Open Water". (b) CTD 759 760 profiles grouped into Clusters II–V. The halocline layer of the water column is enlarged in Figure 7 where 761 Clusters II-V are distinguished. We also present an approximation of thermohaline properties for the 762 downstream Atlantic-modified PrW over the NEW continental slope (dashed red line; adopted from *Falck*, 763 2001) and the profile from Station 172 over the Wandel Sea continental slope (thin black dashed line). The 764 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 765 766 space (thick black dashed line). The panels are shaded according to the corresponding water masses; gray 767 represents the Halostad, while green and pink represent the halocline and define the salinity used for 768 clustering.

Figure 7: 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<sup>-3</sup>. All other designations are similar to those in Figure 6. (e) 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 ITP WETLabs Optical sensor shown for 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

780 Figure 9: (a) Schematic showing formation of the intrusive halocline in clusters III and IV due to 781 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 782 783 curve is approximation of the downstream PrW and AW properties at the Greenland continental slope, the 784 NEW area adopted from (b). The solid dark/light blue curves are approximations of the PcW and upper 785 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  $\sigma_0$  isopycnals in kg m<sup>-3</sup>. (b) 786 787 Temperature and salinity curves for the CTD stations taken in July-August 1993 between 76.5°N and 81°N 788 and west of 5° W over the NEW area after Falck [2001]. Blue circles depict stations from the polynya 789 (shelf) area. Red rectangular depict stations from the Greenland continental slope and Belgica Trough. (a, 790 **b**) Blue shading highlights the approximate properties of the Wandel Sea shelf halocline. The dashed dark 791 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 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"

- 801 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 815 816 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 817 818 2014 taken over the SN/FIIC/NEW area. Red and black circled crosses indicate the CTD stations occupied 819 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 820 Wandel Sea continental slope (> 1000 m depth) during the Norwegian FRAM 2014-15 sea ice drift. The 821 dashed blue rectangle indicates the 2015 study area shown in Figure 3. 822



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 ( $\sim 2$  m to > 4 m thick). Yellow circles identify stations with CTD measurements Blue arrows indicate the northern outlet glaciers of the Flade Isblink Ice Cap.





Figure 4: CTD stations occupied in April-May 2015 (circles). (a) Depth shown by color and blue contour
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from the *TS* analysis. They are identified by their station numbers. Arrows depict deep water pathways.



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Figure 5: Vertical distribution of temperature (red) and salinity (green) profiles over the Wandel Sea shelf 840  $(\geq 100 \text{ m depth}; \text{ solid curves})$  from April and May 2015, over the continental slope (stations 171-173; 841 dashed curves) from June and July 2015 from the Norwegian FRAM 2014-15 ice drift (see Figure 2b for 842 station position) and on the Wandel Sea upper continental slope (ARKXXIII/2 268; dotted curves) from 843 844 RV Polarstern on 2 August 2008 [Kattner, 2009]. Thick red and green lines show typical vertical profiles of 845 salinity and temperature, respectively, for station STN15-68. The blue dashed curve is the in situ 846 temperature of freezing computed using the mean SN salinity profile (not shown). The vertical dashed line depicts salinity of 33 that separates the PcW and AW in the western Beaufort Sea [von Appen and Pickart, 847 848 2012].

![](_page_41_Figure_0.jpeg)

![](_page_41_Figure_3.jpeg)

**Figure 6:** In situ temperature and salinity curves for the CTD stations >100 m depth with  $\sigma_0$  isopycnals presented (dashed grey lines; kg m<sup>-3</sup>). (a) CTD profiles grouped into Cluster I "Open Water". (b) CTD profiles grouped into Clusters II-V. The halocline layer of the water column is enlarged in Figure 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. 

![](_page_42_Figure_0.jpeg)

![](_page_42_Figure_7.jpeg)

Figure 7: 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<sup>-3</sup>. All other designations are similar to those in Figure 6. (e) Temperature and salinity curves
below the glacier depth for the CTD profiles grouped into Cluster V.

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![](_page_43_Figure_4.jpeg)

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**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 ITP WETLabs Optical sensor shown for 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

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![](_page_44_Figure_0.jpeg)

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![](_page_45_Figure_0.jpeg)

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 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  $\pm 1$  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<sup>-3</sup>.