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Key Points:
- Thirteen-year continuous time series demonstrate an overall freshening trend but show seasonal and interannual variability
- Freshening was anomalously high from August 2005 to August 2007 (-0.92 psu or -0.46 psu yr^{-1}) and from August 2009 to August 2013 (-0.66 psu or -0.17 psu yr^{-1})
- Reduced density within the fjord was compensated by a stronger density decrease in the coastal water, which prevented bottom water renewal

Supporting Information:
- Supporting Information S1

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Coastal Freshening Prevents Fjord Bottom Water Renewal in Northeast Greenland: A Mooring Study From 2003 to 2015

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Abstract The freshwater content of the Arctic Ocean and its bordering seas has recently increased. Observing freshening events is an important step toward identifying the drivers and understanding the effects of freshening on ocean circulation and marine ecosystems. Here we present a 13 year (2003–2015) record of temperature and salinity in Young Sound-Tyrolerfjord (74°N) in Northeast Greenland. Our observations show that strong freshening occurred from August 2005 to August 2007 (-0.92 psu or -0.46 psu yr^{-1}) and from August 2009 to August 2013 (-0.66 psu or -0.17 psu yr^{-1}). Furthermore, temperature-salinity analysis from 2004 to 2014 shows that freshening of the coastal water (~range at sill depth: 33.3 psu in 2005 to 31.4 psu in 2007) prevented renewal of the fjord's bottom water. These data provide critical observations of interannual freshening rates in a remote fjord in Greenland and in the adjacent coastal waters and show that coastal freshening impacts the fjord hydrography, which may impact the ecosystem dynamics in the long term.

Plain Language Summary The freshwater content of the Arctic Ocean has increased in recent years in response to climate change, but the impact of freshening on coastal ecosystems, such as fjords, is largely unknown. Freshening is important, as the related change in density can weaken vertical mixing and, subsequently, slow or stop the renewal of the fjord bottom water. Analysis of long-term data (2003–2015) near Young Sound-Tyrolerfjord, a high Arctic fjord in Northeast Greenland, identified anomalously strong freshening events that are at the high end in comparison to other freshening estimates from around the Arctic. Furthermore, the data reveals that renewal of the bottom water was prevented by freshening of the coastal water since 2004–2005. This shift toward fresher coastal water, in combination with freshening of the fjord's basin water, may impact the fjord's ecosystem functioning in the long term. The observations in this study provide new insights into the temporal variability of salinity and temperature and thus provide a critical step toward an impact assessment and identification of underlying processes driving freshening in Northeast Greenland.

1. Introduction

The freshwater content of the Arctic Ocean has increased in recent years in response to climate change (Haine et al., 2015; McPhee et al., 2009; Proshutinsky et al., 2009; Rabe et al., 2011). Alterations of freshwater export from the Arctic Ocean to the subarctic Nordic Seas have the potential to influence surface salinities and impact the rate of dense water formation (Dukhovskoy et al., 2016), with implications for the strength of the Atlantic meridional overturning circulation (e.g., Jahn & Holland, 2013; Rahmstorf et al., 2015), which is a major regulator of the world's climate (Vellinga & Wood, 2002). Recent increases in freshwater fluxes from Arctic glaciers (e.g., Bamber et al., 2012) and general freshening of the coastal domain may also impact Arctic fjords, where freshening can lead to weakened vertical mixing and, subsequently, slow or stop the renewal of bottom water. In extreme cases this could lead to hypoxic or anoxic conditions (Farmer & Freeland, 1983) and ultimately alter the fjord's ecosystem functioning (Diaz & Rosenberg, 2008; Pakhomova et al., 2014).

A vulnerable location to the effects of freshening is the northeast coast of Greenland, where recent evidence from summertime measurements showed local freshening (Sejr et al., 2017). Northeast Greenland's coastal waters receive freshwater from major outlet glaciers such as the Nioghalvfjerdsbrae (79°N), Zachariae

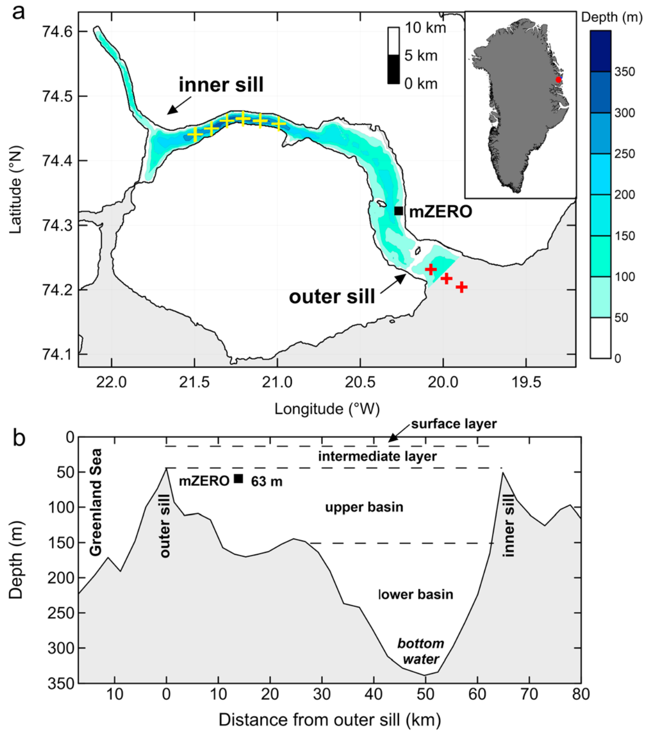

Figure 1. (a) Map of Young Sound-Tyrolerfjord in Northeast Greenland showing the stations and bathymetry (color contours) (Rysgaard et al., 2003). The white areas in (a) depict land, and the gray areas denote the shelf and coastal waters. The black square shows the location of the oceanographic mooring mZERO. The yellow crosses depict the location of CTD stations covering the lower basin, and the red crosses indicate the stations offshore of the outer sill. (b) Bathymetry of the fjord from the coast to the inner parts of the fjord, with the mZERO mooring, outer sill, inner sill, and different fjord layers indicated.

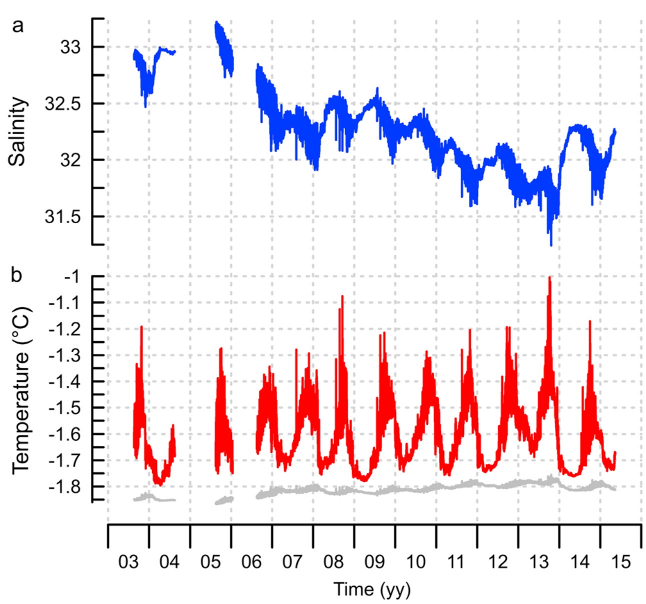

Figure 2. Time series of salinity (a) and temperature (red) and calculated freezing temperature (gray) (b) at 63 m depth at mZERO from August 2003 to May 2015.

Isstrøm, and Storstrømmen glaciers, which connect more than 16% of the Greenland Ice Sheet to the coastal water (Khan et al., 2014) and discharge large amounts of freshwater into the coastal domain. The freshwater export from the Arctic Ocean via Fram Strait forms another source of low density water for the region. Liquid and solid freshwater export via Fram Strait attain approximately 4,000 km^3 yr^{-1} (2000–2010 average; de Steur et al., 2014; Haine et al., 2015) and are transported south via the East Greenland Current along the east coast of Greenland (Håvik et al., 2017; Rudels et al., 2002).

The timing and duration of freshening events cannot be resolved consistently in summertime campaigns; freshening events really can only be resolved through long-term moored monitoring, which provides the temporal resolution necessary to detect subtle shifts in the regional background salinity and are able to reveal interannual differences in freshening rates. This information is critical to aid in projections of future conditions, to asses impacts on ecosystems, and to help identification of the drivers of coastal freshening. Despite their importance, few long-term, continuous hydrographic data sets have been collected along the coast of Greenland, due to the costs and logistical constraints encountered when operating in such a harsh, remote environment (Straneo et al., 2016). This is especially the case in Northeast Greenland where studies have mostly been limited to summer (Håvik et al., 2017; Rysgaard & Glud, 2007; Sejr et al., 2017; Wilson & Straneo, 2015). In this study, we present the first long-term (13 year), continuous moored time series of temperature and salinity of Young Sound-Tyrolerfjord.

2. Data and Methods

2.1. Study Area

Young Sound-Tyrolerfjord is a high latitude (74°N) fjord system in Northeast Greenland that is approximately 90 km long, 2–7 km wide, up to 360 m deep, and covers an area of 390 km^2 (Figure 1a; Rysgaard et al., 2003). The fjord hydrography undergoes a significant seasonal transition. In season 2013–2014, for example, water masses with a relatively large range of salinities (17–33.4) and temperatures (−1.6°C to 8°C) in summer transformed to an almost uniform water mass with near freezing temperatures (~−1.75°C) and a small range of salinity (32.25–32.50) in winter (Boone et al., 2017, Figure 2). Tides are dominated by the semidiurnal lunar constituent (M2), and the tidal range varies between 0.8 and 1.5 m (Rysgaard et al., 2003). Freshwater from the Greenland Ice Sheet and local glaciers enters the fjord through rivers and streams. Total annual river runoff to the fjord system varies between 0.63 and 1.57 km^3 yr^{-1} (Mernild et al., 2007). Young Sound-Tyrolerfjord is covered by land-fast sea ice from mid-October to mid-July. A wind-driven shelf polynya has been observed in the adjacent coastal water during the ice covered period, though it varies in occurrence, location, and size (Pedersen et al., 2010).

A shallow (~45 m depth) outer sill limits exchange between the fjord and the coast to the upper layer which consists mainly of cold (<0°C, except in the surface during summer) and relatively fresh (<34.4) Polar Surface Water (Rudels et al., 2002). Following Farmer and Freeland (1983), we divide the fjord water column into a surface layer (upper 10 m), intermediate layer (from 10 m to sill depth), and the basin water (below sill depth). We further divide the latter into the upper basin water (sill depth −150 m)

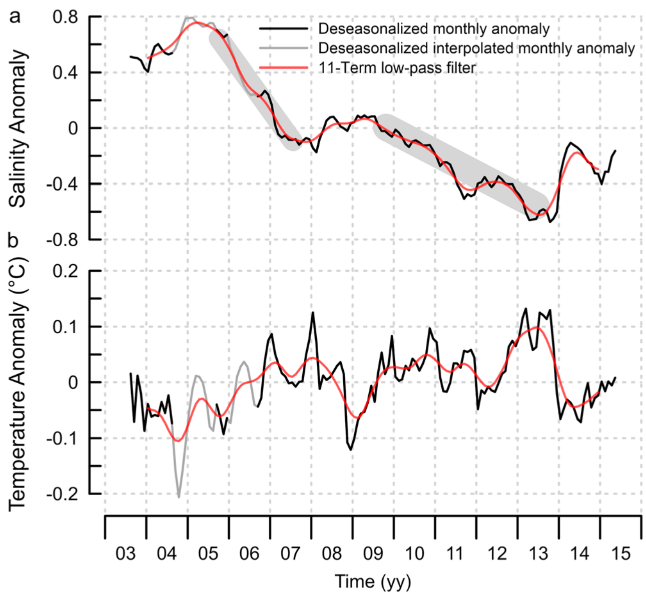

Figure 3. Deseasonalized monthly averaged (a) salinity and (b) temperature anomalies at 63 m from mooring mZERO. The black lines indicate monthly anomalies; the gray line shows interpolated monthly anomalies and the red lines the 11 month low-pass filter of the interpolated monthly anomalies. The gray zones in (a) mark periods with anomalous freshening.

and lower basin water (150–360 m; Figure 1b), which holds the bottom water (>200 m).

2.2. Mooring and CTD Data

The Greenland Ecosystem Monitoring Program has maintained a mooring in Young Sound-Tyrolerfjord, approximately 15 km from the outer sill (74.322°N, 20.269°W, Figure 1). This mooring, referred to as mZERO (Figure 1), has been serviced and redeployed every August from 2003 to 2015. mZERO was equipped with a CTD (Sea-Bird SBE37SMP) located in the upper basin layer (Figure 1). The mean sensor depth was ~63 m depth (±2.7 m; range: 69 m [2008–2009]–62 m [2009–2010; 2012–2013]). The CTD sampling interval varied between 15 and 20 min (2003–2009) to 10 min (2009–2015). Data gaps exist due to mooring malfunction or when redeployment was hampered by ice conditions. Accuracy of the temperature and conductivity sensor is ±0.002°C and ±0.0003 S m^{-1}, respectively. The mooring data resolve the variability of fjord hydrography over a wide range of time scales, from hourly to interannual. In this paper, we focus on interannual variability of the freshening, but note that higher frequency variability is also present and will be examined in a separate paper.

Additionally, the Greenland Ecosystem Monitoring Program conducted CTD transect surveys in Young Sound-Tyrolerfjord from 2004 to 2014 during August using an SBE-19plus CTD (Sea-Bird Electronics, accuracy temperature: ±0.005°C and conductivity: ±0.0005 S m^{-1}). Salinity and temperature data from stations sampled in the lower basin water below 200 m and stations offshore from the outer sill were used to investigate the renewal cycle of bottom water (Figure 1).

3. Results and Discussion

3.1. Temperature and Salinity of the Upper Basin Layer in 2003–2015

The CTD transects between 2004 and 2014 demonstrate that salinity changes at mooring mZERO are representative for salinity changes in the fjord's complete upper basin water (45–150 m depth range, Text S1 in the supporting information). The time series of salinity indicate a freshening trend of the upper basin water (range: 31.2–33.2) (Figure 2). The seasonal evolution of salinity, previously described by Boone et al. (2017), shows significant interannual variability. Observed temperatures varied over a narrow range of −1.78 to −1.0°C (Figure 2). Temperatures close to the freezing point mainly occurred from January to June, while maximum temperatures were observed in late September. Both temperature and salinity time series reveal high frequency oscillations, with seasonally varying amplitudes. Amplitudes were largest when stratification of the fjord was strong, which is mainly from July to December (Boone et al., 2017), and might reflect the influence of internal waves in the fjord basin (Cottier et al., 2004).

Deseasonalized monthly anomalies of salinity (Figure 3), processed according to Thomson and Emery (2014) (Text S2), show the occurrence of a freshening trend of −0.11 psu yr^{-1} (2003–2015) (Table 1). Trend analysis

Table 1
Linear Trends of Deseasonalized Monthly Anomalies of Salinity at Mooring mZERO (August-July), With the Coefficient of Determination (R^2) and Root-Mean-Square Error (RMSE)

Season	August 2003 to March 2015	August 2004 to July 2005	August 2005 to March 2006	August 2006 to July 2007	August 2007 to July 2008	August 2008 to July 2009	August 2009 to July 2010	August 2010 to July 2011	August 2011 to July 2012	August 2012 to July 2013	August 2013 to July 2014
dS dt^{-1} in psu yr^{-1}	−0.11	0.15	−0.51	−0.41	0.14	0.03	−0.14	−0.29	0.06	−0.29	0.56
R^2	0.81	0.70	0.99	0.99	0.83	0.51	0.98	0.98	0.60	0.98	0.96
RMSE	0.17	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.04

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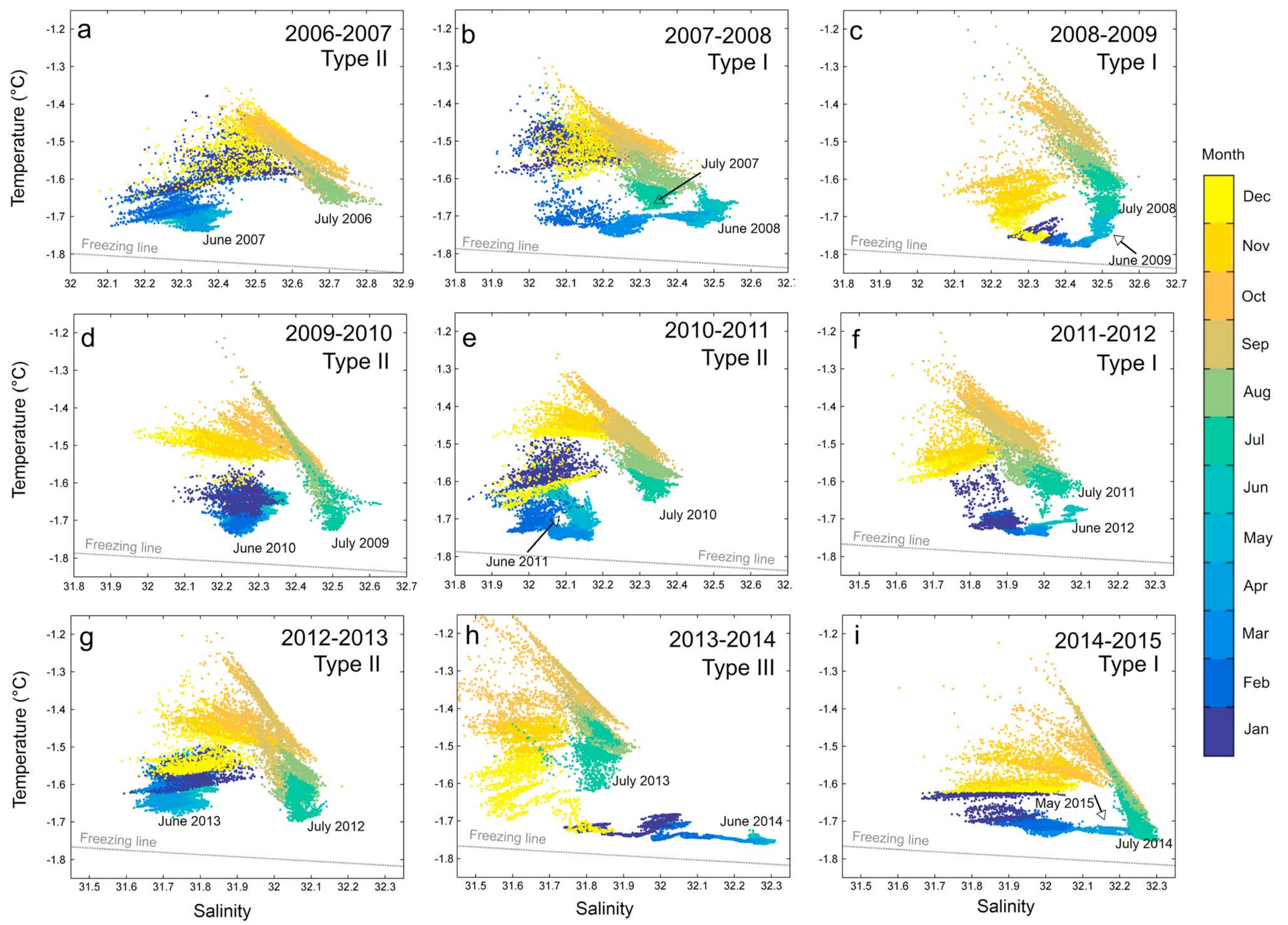

Figure 4. TS diagrams of the seasonal (1 July to 31 June) transformation of hydrography at ~63 m at mooring mZERO in the upper basin water of Young Sound-Tyrolerfjord. The thin lines indicate the freezing line at 63 m. Note that all *y* axes have the same scale (difference between max and min value is constant), but the *x* axes may have different ranges.

of August-August segments reveal that the freshening was mainly caused by anomalous strong freshening from August 2005 to August 2007 (−0.92 psu) and from August 2009 to August 2013 (−0.66 psu). These freshening periods were interrupted by periods when salinity increased as in 2007–2009 (0.16 psu) and 2013–2014 (0.52 psu). Deseasonalized monthly temperature anomalies show only a small warming trend (2003–2015) ($<$0.01°C, P value [5%]: $<$0.001) (Figure 3). We note that a correlation (0.66; P value [5%]: 0.02) exists between trends of August-August segments of salinity and temperature anomalies. Increasing temperatures are therefore correlated with freshening of the basin water.

The general freshening trend from August 2003 to March 2015 (−0.11 psu yr^{-1}) provides an independent verification of the freshening trend of −0.12 psu yr^{-1}, which was based on summer measurements in Young Sound-Tyrolerfjord by Sejr et al. (2017). Other estimates of freshening rates in the Arctic Ocean show freshening rates of −0.04 to −0.2 psu yr^{-1} in the mixed layer between 1972 and 2012, though there are strong regional differences (Peralta-Ferriz & Woodgate, 2015). Hamilton and Wu (2013) reported freshening rates attained −0.02 psu yr^{-1} in the near-surface layer (50–200 m) on the Baffin Island shelf from 1983 to 2003. While comparing different freshening rates is difficult, as they are measured at different depths, locations, and time periods, the aforementioned studies suggest that the freshening rates reported here are at the high end of previously reported values in other Arctic regions.

TS diagrams of the time series of the upper basin water organized as daily averaged TS properties from 2003 to 2015 (Figure S2) and as seasonal plots from 1 July to 31 June show the seasonal transformation of the hydrography in the fjord from 2006 to 2015 (Figure 4). Data collected before 2006 were excluded from Figure 4, as they did not resolve a complete seasonal cycle. Based on the shape in TS space, the seasonal transformations can be grouped in three types. The first type contains years where hydrographic transformations did not lead to a large change in temperature and salinity of the fjord upper basin water. In TS space, these seasons have a circular shape. Years with such patterns are 2007–2008, 2008–2009, 2011–2012, and 2014–2015 (Figure 4). The second type contains years where freshening occurs in the upper basin water leading to a reversed U-shape in TS space and freshening with time. Freshening was observed in seasons 2006–2007, 2009–2010, 2010–2011, and 2012–2013 (Figure 4). Finally, the third type involves a single year (2013–2014) where renewal in the upper basin occurs, indicated by a cold and salty water mass (Figure 4).

The events in 2013–2014 were described by Dmitrenko et al. (2015), who illustrated how the opening of a coastal polynya close to the outer sill impacted the ventilation of the upper basin. As a result, the upper basin was filled with relatively salty (~32.3), oxygen-rich water around the freezing point (~−1.75°C). The associated strong salinity increase (Figures 2 and 3) was unique in the data record, which indicates the unique nature of ventilation by a polynya in Young Sound-Tyrolerfjord.

The TS analysis further emphasizes that freshening occurred in a stepwise manner, not gradually (Figure S2). Freshening is not a linear process and was well captured by the continuous measurements. The fjord hydrography can be impacted by multiple processes, which can act independently, or in concert. These processes include the evolution of the cross-sill salinity gradient, mixing intensity, polynya activity, sea ice processes, and input of low salinity water (Bendtsen et al., 2014; Boone et al., 2017; Dmitrenko et al., 2015). Freshwater input to the coastal waters of East Greenland comprised mainly of freshwater input from land and input of sea ice meltwater (Bacon et al., 2014). During our study period, the ice mass loss rate from the northeastern sector of the Greenland Ice Sheet has accelerated (Khan et al., 2014) and the amount of sea ice exported through Fram Strait has increased (Smedsrud et al., 2017). The observed variation of the seasonal hydrographic transformation of the fjord might be explained by variability of these regional and local processes as they demonstrate a pronounced seasonal cycle and significant interannual variability.

3.2. Temperature and Salinity of the Lower Basin Layer From 2004 to 2014

August values of temperature and salinity of the lower basin water (>200 m depth) (Figure 1) showed that the bottom water has not been renewed since 2004–2005, when salinity changed from ~33.15 (2004) to ~33.25 (2005) (Figure 5a). Instead, stratification in the lower basin increased over time, from nearly uniform salinity in 2004 and 2005 to salinities ranging from 32.75 to 33.05 in 2014. From 2005 to 2014, salinities decreased from ~33.25 (2005) to a minimum of 32.75 (2014), equivalent to maximal freshening rate of 0.056 psu yr^{-1}. This is well below the salinity in 2004 when the previous bottom water renewal took place. Along with decreasing salinities, temperatures increased from ~−1.77°C to ~−1.60°C.

August CTD measurements of coastal water masses near the sill depth (45–60 m) (see Figure 1a for locations) show that in 2004 and 2005 the densities of the lower basin water and water masses at sill depth were comparable (Figure 5b). This changed after 2005, when freshening decreased densities in the coastal water below densities in the lower basin (Figure 5b). The largest change in density of the offshore water masses at sill depth was recorded from 2005 to 2007. During that period, the mean salinity changed from 33.3 to 31.4. Since 2007, mean salinities increased and varied between 32.0 and 32.6, which was still below salinities of the lower basin.

Young Sound-Tyrolerfjord is connected to the Polar Surface Water layer of the coastal water via a shallow outer sill. Major replacements of the basin water will occur whenever the coastal water exchanged over the sill exceeds the density of water within the fjord basin (Farmer & Freeland, 1983). The inflow to the upper basin water recorded in 2013–2014 was not dense enough to renew the lower basin water of the fjord; only partial basin renewal occurred and only impacted the upper basin of the fjord (Dmitrenko et al., 2015). Although our time series contain only one observation of renewal, the offshore water masses near sill depth clearly show a decrease in density of the coastal water during our observational period. As no significant increasing linear trend in discharge volumes from the main river of the fjord's catchment was observed during the study period (Sejr et al., 2017), our observations suggest that the lack of renewal and freshening of the upper basin water could be caused by freshening of the coastal water. The increasing stratification of lower basin water indicates that downward transport of low density water is dominated by turbulent diffusion or by mixing due to internal waves, which are commonly observed in fjords (Cottier et al., 2010; Mortensen et al., 2011).

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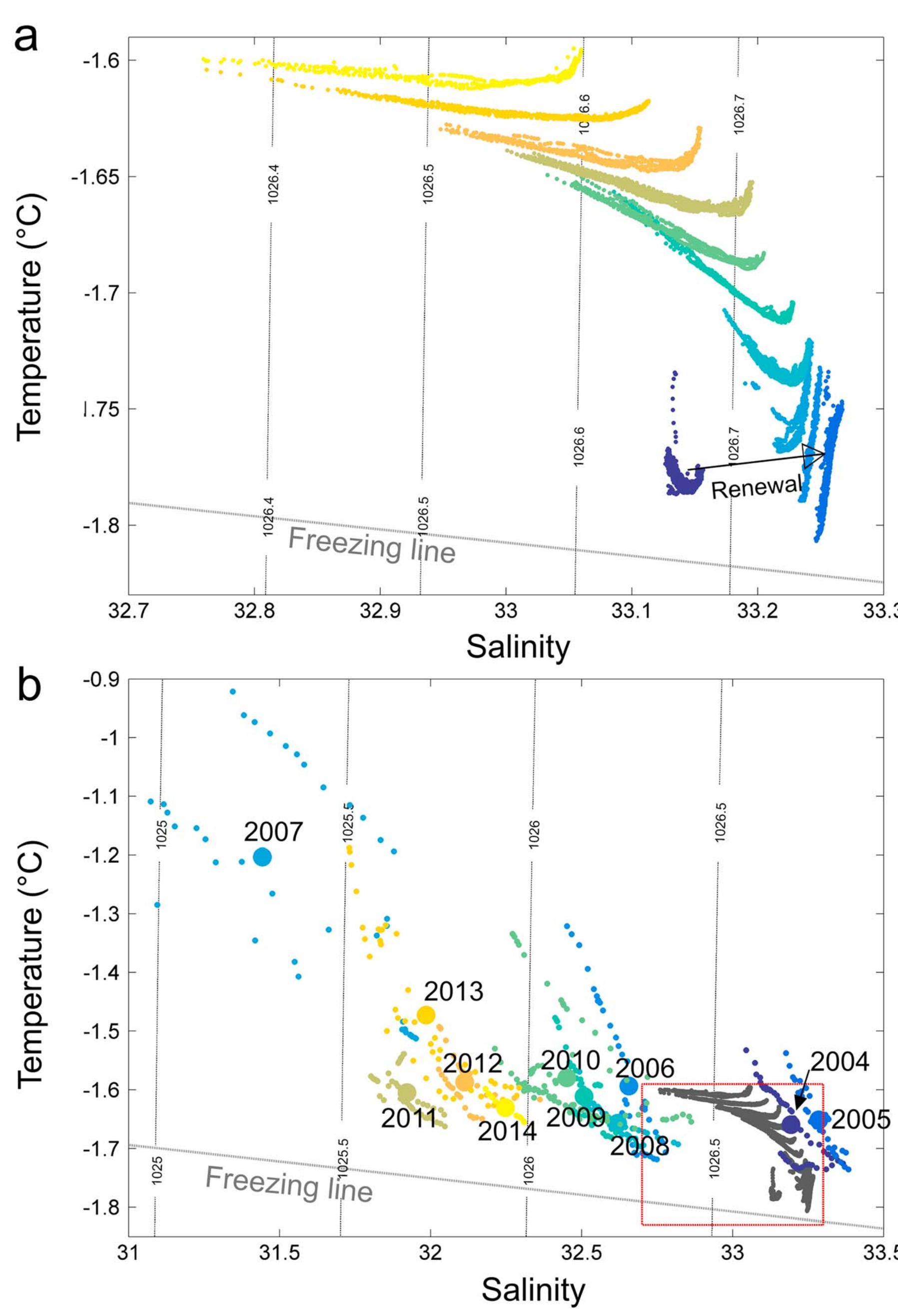

Figure 5. TS diagram of (a) the lower basin water (>200 m) of Young Sound-Tyrolerfjord from August measurements 2004 to 2014 and (b) TS diagram of the offshore water masses around sill depth (45–60 m) and their means (large dots), including the data from (a) in black. The red box in (b) shows the limits of the TS diagram in (a). Thin lines in (a) and (b) indicate the freezing line at the surface (0 m) and isopycnals; locations of the measurement are specified in Figure 1.

3.3. Outlook

Changes in salinity can influence marine ecosystems in several ways. Salinity influences alkalinity (buffer capacity) and calcium ion concentrations, impacting the vulnerability of fjord's to ocean acidification (Arctic Monitoring and Assessment Program (AMAP), 2013), and changes in density-driven circulation can influence nutrient availability for primary production in fjords (Meire et al., 2016, 2017). Furthermore, in Young Sound-Tyrolerfjord, glacial meltwater runoff and input of freshwater from outside the fjord can influence the composition of the bacterial community (Paulsen et al., 2017), as well as the phytoplankton grazer community (Middelbo et al., 2017). A lack of renewal, due to a more stable halocline, may over time lead to lower oxygen concentrations or even lead to hypoxic conditions in the bottom water. This may impact biogeochemical cycling and the distribution and composition of the benthic fauna (Rysgaard & Glud, 2007).

More research is needed to identify the drivers of the coastal freshening. Both regional warming and increased mass loss from the Northeast Greenland Ice Sheet have been reported (Khan et al., 2014). Furthermore, results from Cox et al. (2010) suggest that increasing freshwater from sea ice melt along the coast of East Greenland might be important, as the anomalously strong freshening reported here coincides with a strong increase in sea ice meltwater input to the East Greenland Current in 2005–2007 (Cox et al., 2010). However, the pathways of freshwater transport and the specific processes involved in the freshening of the coastal water of Northeast Greenland remain unclear, which stresses the importance of dedicated long-term observational studies in this region.

4. Conclusions

A 13 year moored time series of salinity and temperature near the outer sill of Young Sound-Tyrolerfjord in Northeast Greenland enables us to investigate the interannual evolution of salinity and temperature of the basin water and to quantify the impact of freshening on the fjord's hydrography. Interannual variability of salinity in the upper basin water indicates a general freshening trend of -0.11 psu yr^{-1}. Freshening was anomalously high from August 2005 to August 2007 (-0.92 psu or -0.46 psu yr^{-1}) and from August 2009 to August 2013 (-0.66 psu or -0.17 psu yr^{-1}). Although the salinities within the fjord have decreased significantly, the reduced density was compensated for by an even stronger freshening of the coastal water. This prevented renewal of the bottom water since 2004–2005. A shift toward fresher coastal water and the subsequent lack of bottom water renewal in combination with general freshening of the fjord basin water may impact the fjord's ecosystem functioning. The observations in this study provide new insights into the temporal variability of salinity and temperature and thus provide a necessary step toward an impact assessment and identification of underlying processes driving freshening in Northeast Greenland.

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