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ORIGINAL RESEARCH ARTICLE

Increases in the temperature and salinity of deep and intermediate waters in the West Spitsbergen Current region in 1997—2016

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Summary This study investigated the temporal variability in the basic physical properties of deep and intermediate waters in the West Spitsbergen Current region at 76°30'N latitude from 1997 to 2016. Emphasis was placed on quantifying the changes in temperature and salinity and determining the potential drivers of these changes. Hydrographic data were obtained during annual summer cruises aboard the r/v *Oceania* in the Nordic Seas. The increase in the water temperature, which was especially strong in the western part of the investigated section, was associated with considerable changes in the water layers salinity. The temperature and salinity of the intermediate water increased much faster (0.021°C yr^{-1} and 0.0022 yr^{-1}, respectively) than those of the deep water (0.009°C yr^{-1} and 0.0004 yr^{-1}, respectively). The warming rate in the upper 2000 m was also higher than the mean warming rate of the global ocean. The source of the deep water temperature and salinity increases was the deep water inflow from the Arctic Ocean into the Greenland Sea. In contrast, the increase in these properties in the intermediate water was associated with the advection of warmer and more saline Atlantic Water from the North Atlantic to the Nordic Seas.

1. Introduction

In recent years, oceanographers and climatologists have been increasingly focused on ocean warming and the ocean's importance as a buffer that stores excess energy trapped on the Earth via the greenhouse effect. The global ocean has absorbed 93% of this additional heat since 1970 (Rhein et al., 2013), and the rate of change in the ocean heat content (OHC) is a good indicator of radiation imbalances at the top of the atmosphere (Church et al., 2013). Due to its enormous heat capacity, the global ocean is the

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flywheel of the climate system, absorbing, storing and redistributing heat over long time scales and large spatial scales. The average global ocean temperatures are less variable than land temperatures, which can change rapidly from year to year (Wijffels et al., 2016).

Solar radiation is absorbed in the euphotic zone of the ocean, and the absorbed heat is distributed over the mixed layer depth (MLD). In most of the ocean, the MLD does not exceed 100 m; in only the subpolar and polar zones in winter does the MLD exceed 200 m. However, recent studies have shown that heat accumulates not only in the ocean surface layer but also in intermediate and deep waters (e.g., Desbruyères et al., 2016, 2017; Levitus et al., 2012; Purkey and Johnson, 2010; Roemmich et al., 2015). According to Levitus et al. (2012), from 2003 to 2010, the heat content in the upper 700 m increased more slowly than it did in the previous decade, while the absorption of heat at depths between 700 and 2000 m did not weaken during this period. The 700—2000 m ocean layer absorbed approximately one-third of the heat absorbed by the upper 2000 m of the global ocean. This suggests that the ocean's deeper layers reduce the surface layer warming by absorbing the excess heat accumulated in the surface layer. The warming of the ocean between 700 and 2000 m depth from 2006 to 2015 accounted for 50% of the total increase in the ocean's heat content (from 0 to 2000 m) (Desbruyères et al., 2016), which is more than 20 percentage points higher than the long-term estimate (1955—2010) made by Levitus et al. (2012).

A better understanding of the temporal changes occurring in intermediate and deep waters is critical due to the important role that these layers play in the global climate system. Deep water formation processes are very important for global thermohaline circulation forcing, and these processes occur mainly at high latitudes. The Arctic Ocean and the Nordic Seas compose one of the most important regions for deep water formation in the world ocean. Thermohaline circulation plays two very important roles: it regulates climate by distributing heat globally and it supports marine life by providing well-oxygenated and nutrient-rich water (Rahmstorf, 2002).

Increases in the temperature and salinity of the intermediate and deep waters in the Nordic Seas have been observed and analyzed by, for example, Holliday et al. (2008), Latarius and Quadfasel (2010, 2016), Langehaug and Falck (2012), Rudels et al. (2012), Somavilla et al. (2013), von Appen et al. (2015), Wang et al. (2015), Walczowski et al. (2017), Jeansson et al. (2017), Lauvset et al. (2018) and Brakstad et al. (2019).

This study aims to analyze increases in temperature and salinity observed in intermediate and deep waters in the West Spitsbergen Current (WSC) region. The heat stored in this area and transported by the WSC to the Arctic Ocean may have a high influence on Arctic sea ice melting and climate change. We believe that the results described in this work complement the current understanding of the intermediate and deep water properties in this area.

2. Study area

The Nordic Seas, located north of the Greenland-Scotland Ridge and south of the Fram Strait, include the Greenland, Norwegian, and Iceland Seas (Fig. 1). The Greenland-Scotland Ridge separates the Nordic Seas from the North Atlantic, and the Fram Strait, situated between Greenland and Svalbard, is the only deep connection ($\sim$ 2600 m) between the Nordic Seas and the Arctic Ocean. The Nordic Seas are a primary region for high-latitude water mass transformation, where strong vertical mixing induced by heat loss to the atmosphere converts most of the incoming subtropical warm and saline Atlantic Water (AW) into dense overflow water (e.g., Latarius and Quadfasel, 2016). Atlantic Water inflows to the Nordic Seas with the North Atlantic Current (NAC) through the Greenland-Scotland Ridge; then, it continues as the Norwegian Atlantic Current (NwAC) (Hansen and Østerhus, 2000; Orvik and Niiler, 2002) and as two branches of the West Spitsbergen Current (WSC) (Piechura and Walczowski, 1995). The eastern WSC branch transports AW along the Barents Sea/Svalbard Shelf break into the Arctic Ocean, while the western WSC branch transports AW over the Mohn and Knipovich ridges, where it recirculates westward and southward (Piechura, Walczowski 1995). Additionally, a significant portion of the AW that inflows into the Fram Strait recirculates to the south (Schauer et al., 2004). The flows of the western branch of the WSC create the border between the Arctic-origin water masses (Arctic domain) to the west and the Atlantic-origin water masses (Atlantic domain) to the east (Swift and Aagaard, 1981; Walczowski, 2013). The border between the Atlantic domain and the Arctic domain is the Arctic front, whose location is closely related to the bottom topography. The midocean ridge system of the Mohn and Knipovich ridges creates a natural barrier separating the waters of Atlantic and Arctic origin. Located at latitudes of 70—73°N, the Mohn Ridge stretches towards the northeast. The northern extension of the Mohn Ridge — the Knipovich Ridge — stretches north towards the Fram Strait (Raj et al., 2019).

There are various definitions of Atlantic Water. In this region, it is often defined as water warmer than 0°C and more saline than 34.92 (Walczowski, 2014). The maximal thickness of the defined AW layer does not exceed 700 m in the Atlantic domain and 500 m in the Arctic domain. The Arctic Intermediate Water (AIW), located below the AW layer, is formed within the convective gyres in the Arctic domain of the Nordic Seas (Blindheim, 1990; Jeansson et al., 2017; Swift and Aagaard, 1981) as a result of the cooling of the warm, saline AW and subsequent mixing with the colder, fresher Polar Water found to the west of the Greenland Sea Gyre (Lauvset et al., 2018). Beneath the intermediate layer, Norwegian Sea Deep Water (NSDW) occurs. NSDW is formed by the mixing of Greenland Sea Deep Water (GSDW) and deep water from the Arctic Ocean. NSDW is the densest water mass in the Norwegian and Iceland seas but is also found in the northern and eastern parts of the Greenland Sea. Part of the AIW and NSDW advects from the Greenland Sea northward to the West Spitsbergen Current region, gradually changing its properties as a result of interactions with other water masses (Swift and Koltermann, 1988).

Since the 1980s, the renewal of deep water in the Greenland Sea has decreased considerably (Schlosser et al., 1991). Only the intermediate layer has been ventilated, contributing to the lower limb of the Atlantic meridional overturning circulation (Eldevik et al., 2009; Karstensen et al., 2005). The relatively cold and fresh deep

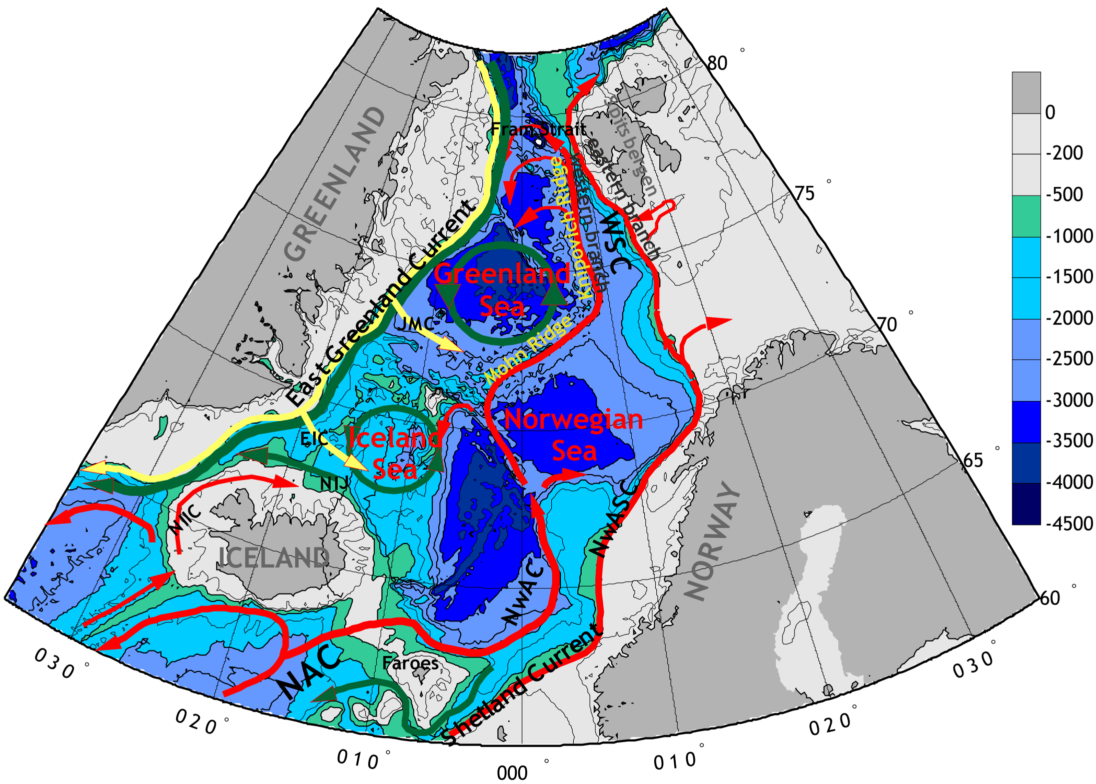

Figure 1 Map of the Nordic Seas with bathymetry and circulation patterns. Red and yellow arrows indicate warm Atlantic Water inflow and cold and fresher outflow, respectively. Green arrows indicate cold, dense water circulation. The acronyms are the East Icelandic Current (EIC), the Jan Mayen Current (JMC), the North Atlantic Current (NAC), the North Icelandic Irminger Current (NIIC), the North Icelandic Jet (NIJ), the Norwegian Atlantic Current (NwAC), the Norwegian-Atlantic Slope Current (NwASC), and the West Spitsbergen Current (WSC).

water in the Greenland Sea (GSDW) is modified by the advection of warmer and more saline deep water from the Arctic Ocean. Eurasian Basin Deep Water (EBDW) is Arctic Ocean deep water that is dense enough to mix with the deep water in the Greenland Sea and leaves the Arctic Ocean below 2000 m depth. Therefore, in the absence of deep convection providing fresher and colder waters below 2000 m, EBDW accumulates in the deep Greenland Sea, increasing the temperature and salinity (Somavilla et al. 2013).

3. Data and methods

In this work, we used data collected by the long-term AREX program. For the last 30 years, the Institute of Oceanology, Polish Academy of Sciences has performed annual cruises aboard the r/v *Oceania* to the Nordic Seas and Fram Strait (Walczowski et al., 2017). Since 2000, the data have been collected in the same array in the same season (June—July) and processed in the same way. The samples constituting the longest time series were collected from section N, situated along the 76°30'N parallel between 4°E and 14°E longitude (Fig. 2); therefore, this section was selected for further analysis.

Water masses are mainly defined based on temperature and salinity (or density) criteria, so the temporal variability in their properties strongly depends on the adopted parameterizations. Therefore, in this study, the mean temperature and salinity, as well as the heat content, were calculated for selected depth layers. Water between 0 and 500 m was defined as surface water, water between 500 and 1000 m was defined as intermediate water, and water below 1000 m was defined as deep water. The mean values of the water properties were calculated for the whole section as well for the Arctic Water and Atlantic Water domains, which are represented by stations N-8 (76°30'N, 6°E) and N-1 (76°30'N, 10°E), respectively.

The CTD measurements were performed using an SBE 911plus probe and covered the whole water column from the surface to the seafloor. The accuracy of the temperature, conductivity and pressure measurement was $\pm$ 0.001°C, $\pm$0.0003 S/m and $\pm$0.015% of full scale, respectively, sufficient for the analysis of the temperature and salinity changes in the intermediate and deep waters. Standard procedures provided by the manufacturer of the SeaBird system (software modules SeaSave and SBEDataProc) were used for collection, processing and quality control of the hydrographic data.

Interpolation, quantitative data analysis and statistical calculations were performed in MATLAB, while dedicated software (Ocean Data View (Schlitzer, 2015)) was used to visualize the processed data. The mean water properties

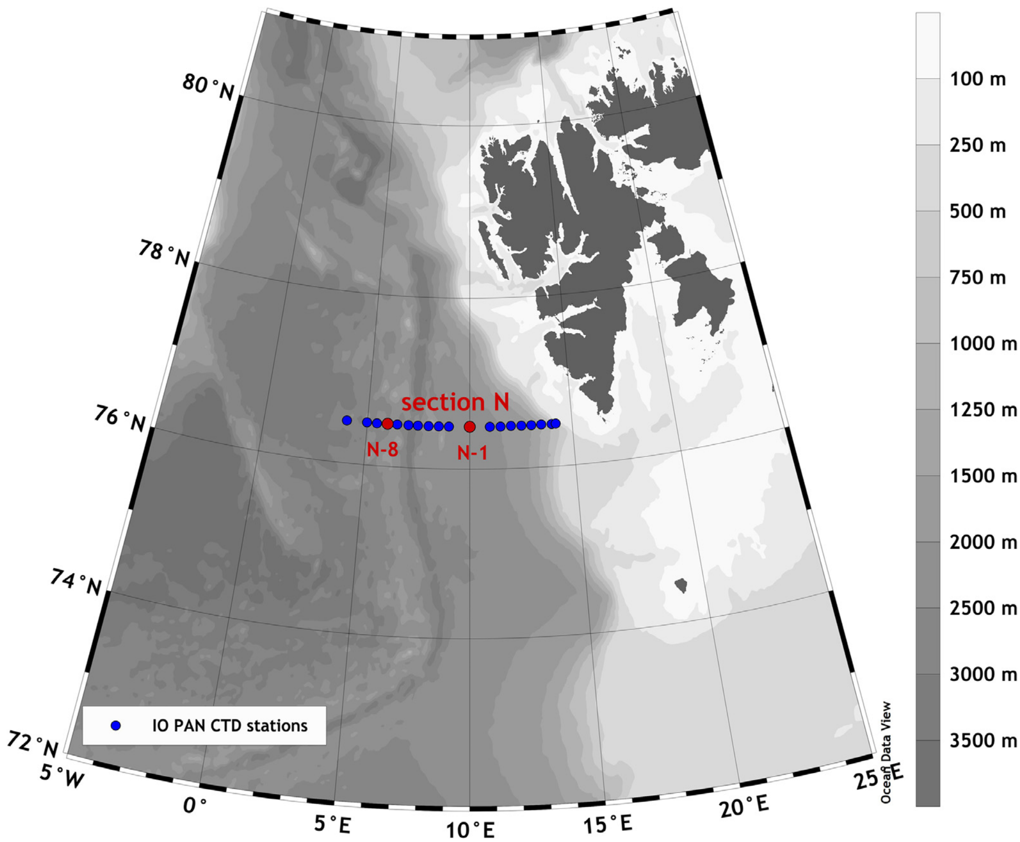

Figure 2 CTD stations along section N sampled every summer during the AREX observational program carried out by IO PAN in the period 1997—2016.

and heat content in each water layer were calculated from temperature and salinity fields interpolated onto a regular grid with the horizontal and vertical resolution of 0.1 degree and 1 m, respectively. The data were interpolated using the MATLAB griddata function, applying the linear interpolation method. All the analyzed trends presented below are statistically significant, with a p-value < 0.01.

The heat content (H) was calculated for the surface, intermediate and deep water layers, as well as the entire water column:

$$H = \int_{h2}^{h1} \rho C p \theta dz. \quad (1)$$

The average water density (ρ), heat capacity (Cp) and potential temperature (Θ) of each layer were used; *h1* and *h2* are the depth range over which the heat content was computed.

4. Results and discussion

The distributions of potential temperature and salinity along section N in the summer seasons of 1997 and 2016 are shown in Figure 3. The intermediate and deep waters were much warmer and more saline in 2016 than in 1997. The average -0.80°C isotherm depth was 1200 m in 1997 but 1700 m in 2016, a reduction of 500 m over 20 years. The greatest increases in potential temperature and salinity were observed in the western part of the section, in the Arctic domain.

The temporal changes in the water properties varied with depth. The potential temperature trend reached 0.045°C yr^{-1} in the surface layer (Tab. 1) (Fig. 4). The temporal variability in the surface water temperature was very high, with three pronounced maxima in 1999, 2006, and 2014. The salinity trend reached 0.0051 yr^{-1}, with clear maxima in 2006 and 2014 (Fig. 5). The potential temperature of the intermediate water increased more slowly (0.021°C yr^{-1}) than that of the surface layer, but the temporal variability was still evident. The slowest warming occurred in the deep water, with a stable linear increase of 0.009°C yr^{-1} without major interannual variations (Fig. 4). The same patterns were observed for the salinity of the intermediate water (0.0022 yr^{-1}) and deep water (0.0004 yr^{-1}) (Fig. 5). The observed trends along section N confirm the positive temperature and salinity trends observed in the eastern Nordic Seas (Larsen et al., 2016; Walczowski et al., 2017).

The changes in water properties were not uniform along the whole section. Hovmöller plots of potential temperature at stations N-8 (76°39'N, 6°E) and N-1 (76°30'N, 10°E) show differences between these two stations (Fig. 6). The changes in the intermediate and deep water temperatures in the Arctic domain occurred more quickly than those in the Atlantic domain. At the station in the Arctic domain (N-8), after 2009, the potential temperature of the deep and

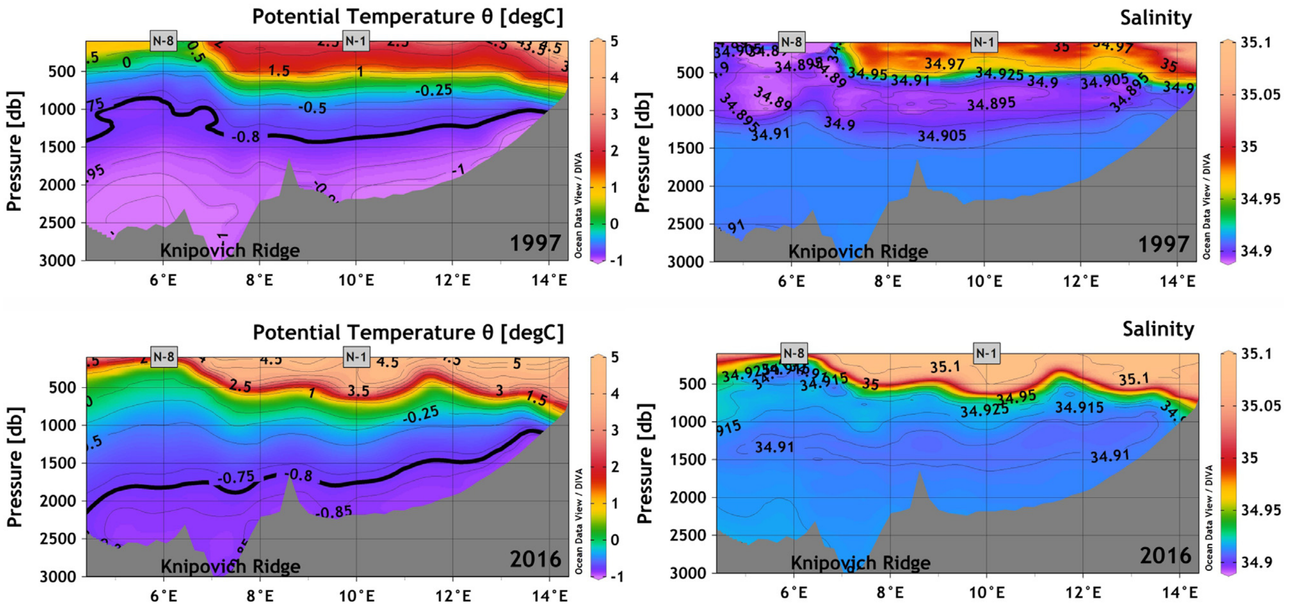

Figure 3 Distributions of potential temperature (left) and salinity (right) along section N in the summer seasons of 1997 (upper) and 2016 (lower). The bold line shows the −0.8°C isotherm.

Table 1 Trend analysis of temperature and salinity in the surface, intermediate and deep water layers from 1997 to 2016.

Pressure [db]	Temperature			Salinity		
	Slope	R^2	p-value	Slope	R^2	p-value
0—500	0.045	0.34	0.0075	0.0051	0.66	0
500—1000	0.021	0.37	0.0046	0.0022	0.73	0
1000—bottom	0.009	0.91	0	0.0040	0.44	0.0014

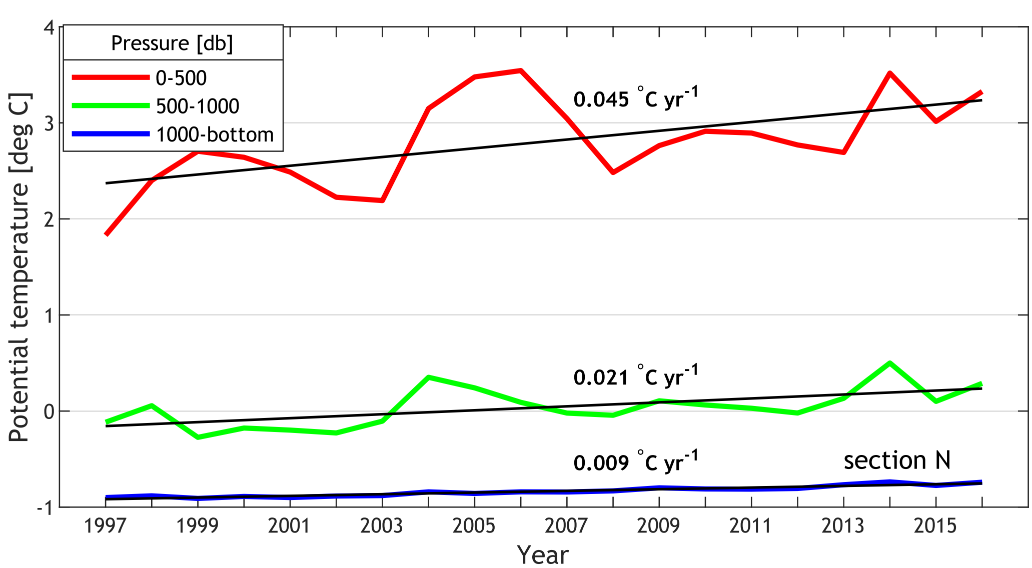

Figure 4 Mean potential temperature of the surface, intermediate and deep waters across section N from 1997 to 2016.

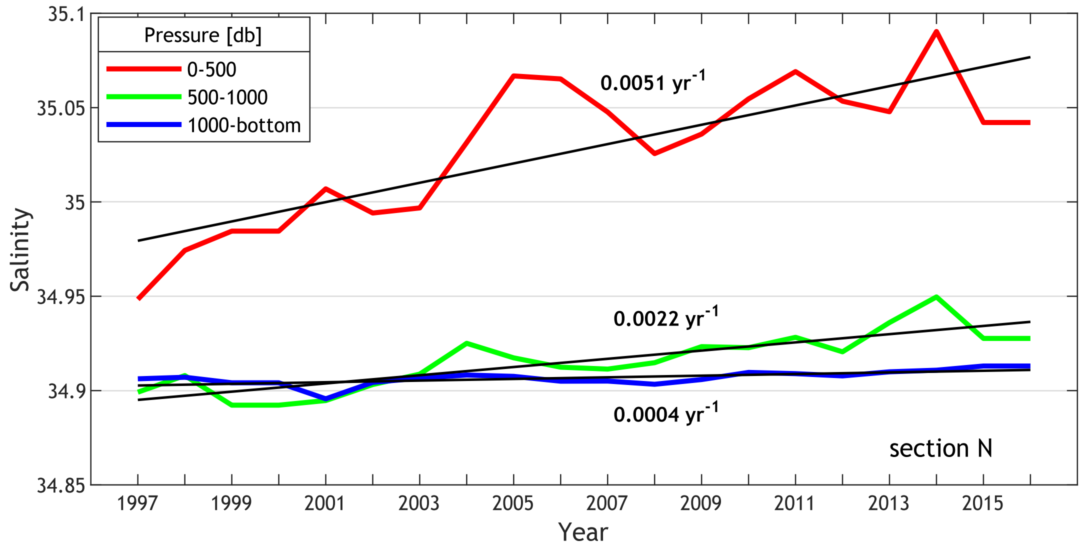

Figure 5 Mean salinity of the surface, intermediate and deep waters across section N from 1997 to 2016.

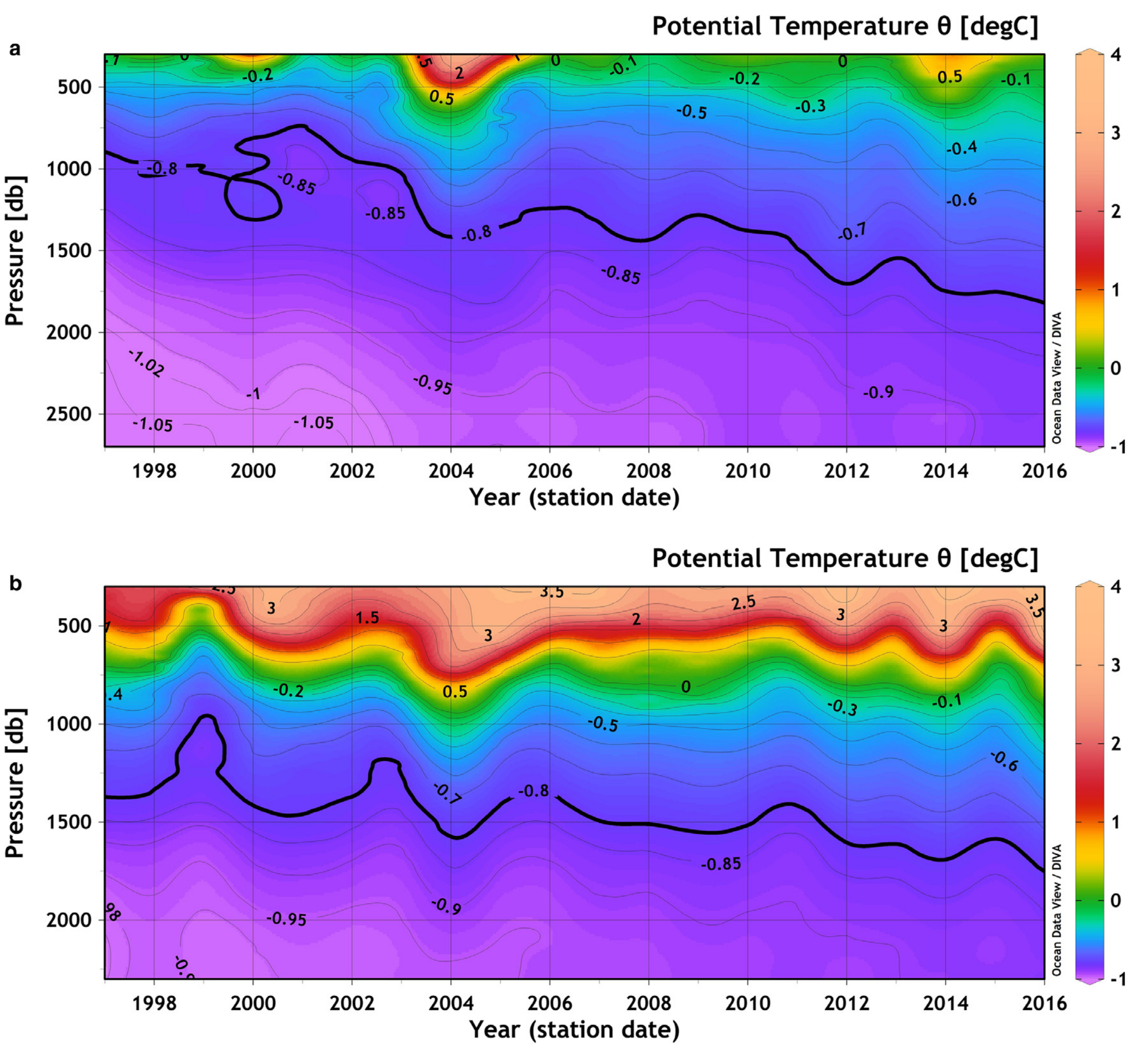

Figure 6 Hovmöller plot of potential temperature at stations N-8 (upper) and N-1 (lower) from 1997 to 2016. The bold line shows the −0.8°C isotherm.

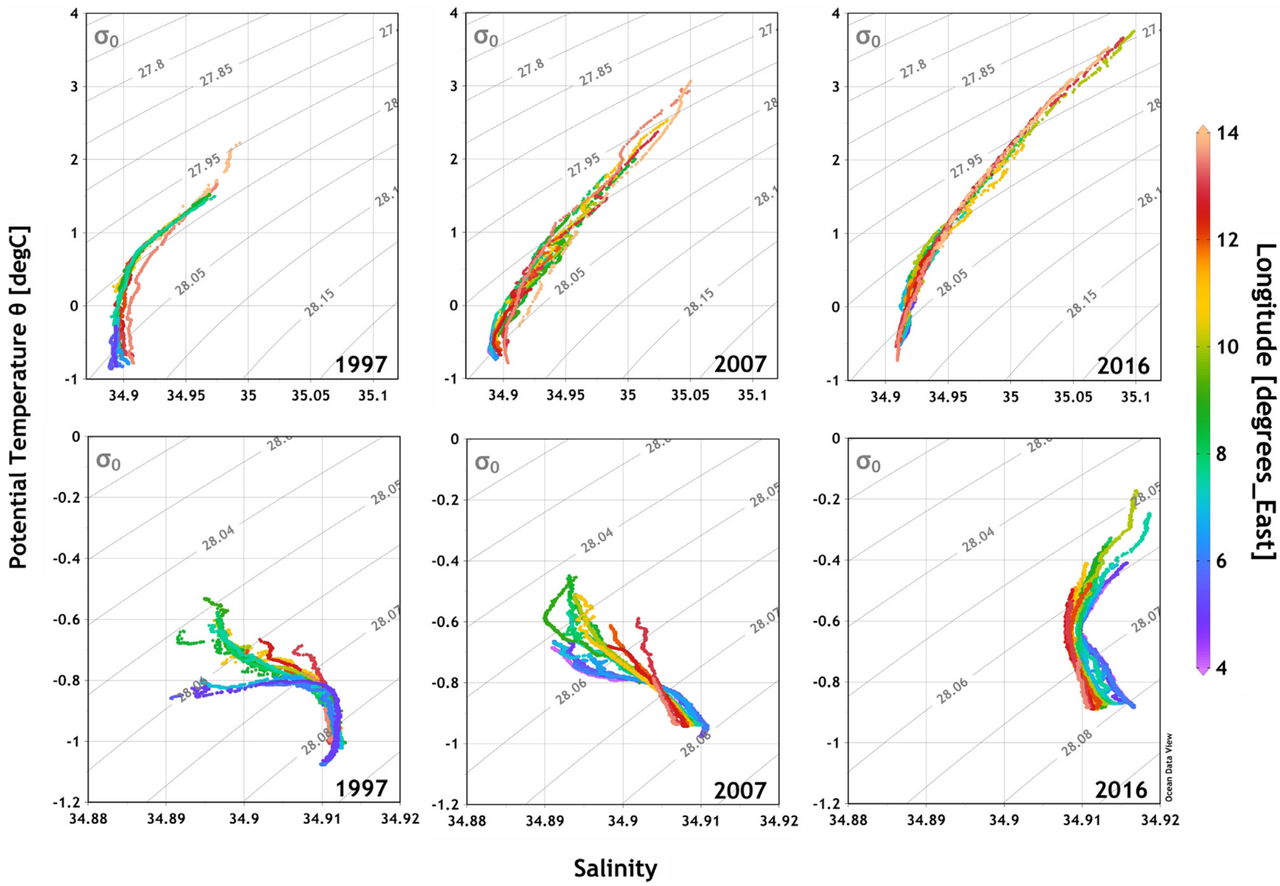

Figure 7 Θ-S diagrams of intermediate (upper panels) and deep (lower panels) water along section N in 1997, 2007 and 2016. Note the differing temperature and salinity scales between the two panels. The color scale indicates the eastern longitude.

intermediate waters did not exceed −0.95 and −0.8°C, respectively. The bottom water potential temperature was −1.08°C in 1997 and −0.87°C in 2016 (Fig. 6), reflecting an increase of 0.21°C in the last 20 years. In the Atlantic domain (N-1), the potential temperature of the deep water did not exceed −0.95°C after 2005, four years earlier than this temperature was observed in the Arctic domain (N-8), while the potential temperature of the intermediate water did not exceed −0.7°C. The lowest potential temperature of deep water was −1.01°C in 1997 and −0.87°C in 2016 (Fig. 6). This means that the lowest potential temperature at this station increased by 0.14°C in the last 20 years and was 0.07°C less than that in the Arctic domain (N-8).

The Θ-S diagrams presented in Figure 7 show the relationship between the potential temperature and salinity along section N in the intermediate (500—1000 m) and deep (> 1000 m) waters in 1997, 2007, and 2016. The upper Θ-S diagrams show the significant influence of sinking Atlantic Water on the intermediate water, especially in the eastern part of the section. In 1997, the intermediate water (500—1000 m) was characterized by salinity below 35 and potential temperatures below ~2°C. In 2007, the maximum salinity was 35.05, and the potential temperature reached 3°C, while in 2016, the maximum salinity was 35.1, and the potential temperature was almost 4°C. The lower Θ-S diagrams show that in 1997, the properties of the deep water varied among the western, central and eastern parts of section N. The western part (purple-blue dots) was the least saline and the coldest, the central part (green dots) was the warmest, and the eastern part (orange-red dots) was the most saline. In subsequent years, the deep water became more homogeneous as its potential temperature and salinity continuously increased.

This 20-year time series of continuous, consistent oceanographic data provides a valuable basis for analysis. It reveals significant summer-to-summer changes in the basic water properties in the West Spitsbergen Current region. The greatest variability occurred in the surface layer and decreased with depth. There were positive trends in both temperature and salinity in all layers. The rates of the annual salinity and temperature increases also decreased with depth. All these trends were statistically significant. However, this time series is still too short to determine the causes of these changes or to separate natural variability from that resulting from progressive climate change. The flow in the surface layer of the investigated region is dominated by the Atlantic meridional overturning circulation (AMOC), and the changes are mostly advective in nature.

The long-term changes in poleward oceanic fluxes are associated with the Atlantic multidecadal oscillation, which has a period of 60-80 years (Delworth and Mann, 2000).

The intermediate and deep waters of the studied region mostly inflow from the central part of the Greenland Sea (Swift and Koltermann, 1988). Therefore, the increases in temperature and salinity in the deep and intermediate waters along section N are closely related to the changes observed in the central part of the Greenland Sea (Brakstad et al., 2019; Latarius and Quadfasel, 2016; Lauvset et al., 2018). This is most clearly observed in the western part of the area (Arctic domain), which is located in the north-eastern part of the Greenland Sea. The water supply to this area from the west is unimpeded over the entire water column. The flow of water to the eastern part (Atlantic domain), which is located in the northern part of the Norwegian Sea, is to some extent blocked by the Knipovich Ridge. Therefore, mostly in this area, the pattern of changes in the 500—1000 m layer is similar to that in the surface layer. Nevertheless, connections with the inflow of AW to the Nordic Seas are also important for the intermediate and deep layers in the western part of the studied region. Holliday et al. (2008) found that the freshening trend in the upper ocean of the northeastern North Atlantic and Nordic Seas in the 1960s—1990s had reversed and that since that period, temperature and salinity have rapidly increased in the Atlantic Water inflow to the Nordic Seas. After 2000, stronger ventilation was observed in this area, which is associated with the advection of warmer and more saline surface water flowing from the North Atlantic (Lauvset et al., 2018). The advection of Atlantic origin water resulted in stronger ventilation in the Greenland Sea (Brakstad et al., 2019; Lauvset et al., 2018). However, convection still reached only intermediate depths, enabling ventilation and refreshing the water in the intermediate layer. This contributed to much greater increases in temperature and salinity in this layer than in the deep layer (Brakstad et al., 2019; Latarius and Quadfasel, 2016; Lauvset et al., 2018).

The source of warming in the deep Greenland Sea is the inflow of deep water from the Arctic Ocean. The relatively warm and salty Eurasian Basin Deep Water flows into the colder and less saline Greenland Sea Deep Water (Aagaard et al., 1985). This inflow is possible due to the cessation of deep convection in the central part of the Greenland Sea in the 1980s, which provided cold and deep saline water below 2000 m (Schlosser et al., 1991). The rate of deep water warming is not the same for the entire Nordic Seas region. Deep water in the central Greenland Sea warms rapidly because it has direct contact with deep water flowing from the Arctic Ocean. The deep waters of the Norwegian and Iceland Seas are warming at a slower rate because they are products of the mixing of their own ambient waters with GSDW and Arctic outflow water (González-Pola et al., 2018; Rudels et al., 2012). According to Somavilla et al. (2013), in the absence of deep convection, deep water from the Arctic Ocean will flow into the deep parts of the Greenland Sea, making them warmer and more saline until they reach the properties of the deep water from the Arctic Ocean. The rate of EBDW import from the Arctic Ocean into the central Greenland Sea increased from 0.12 Sv before the 1980s (Bönisch and Schlosser, 1995) to ~0.44 Sv in 1993—2009 (Somavilla et al., 2013). Assuming that the current trend will remain unchanged, the GSDW will have the same properties as the Arctic Ocean deep water in approximately 2025 (Langehaug and Falck, 2012; Somavilla et al., 2013).

As mentioned above, one cannot say with certainty whether the causes of these changes are natural or anthropogenic. Indisputably, we are observing an increase in temperature in the WSC region and subsequent changes in the regional ecosystem (Dąbrowska et al., 2020; Stempniewicz et al., 2007; Węsławski et al., 2011). In the context of global warming, the temperature increase in all layers is an important and concerning phenomenon. The increasing concentrations of greenhouse gases in the atmosphere warm the Earth's climate system. The ocean contains over 50 times more carbon dioxide (the main greenhouse gas) than the atmosphere, and cold deep waters serve as its main reservoir (Stewart, 2008). Warming of the deep ocean layer could release large amounts of carbon dioxide into the atmosphere, intensifying the greenhouse effect. Moreover, the thermal expansion of water (the steric effect) leads to increased sea levels and, in addition to the loss of glacial mass, accounts for approximately 75% of global sea level rise since the 1970s. From 1993 to 2010, the average global sea-level rise was estimated at ~2.8 mm yr^{-1}, of which oceanic thermal expansion accounted for ~1.1 mm yr^{-1} (Stocker et al., 2013).

The progressive increase in the OHC may suggest that, in addition to natural variability, climate change caused by the greenhouse effect is an important driver of the observed warming. The world ocean accounts for approximately 93% of the warming of the Earth system that has occurred since 1955 (Levitus et al., 2012). For the years 1955—2010, the heat content of the world ocean in the 0—2000 m layer increased by 24.0 10^{22} J, corresponding to a rate of 0.39 W m^{-2} per unit area of the world ocean and a volume mean warming of 0.09°C. This has resulted in a temperature increase of 0.006°C yr^{-1}. Over the decade (2007—2016) of continuous observations, the mean surface-to-bottom ocean warming was 0.0022°C yr^{-1}. This temperature change is equivalent to a heat uptake of 0.71 W m^{-2} over the surface of Earth, approximately 1 W m^{-2} per unit area of the world ocean. The global ocean is warming at all depths, with warming maxima at the surface, 1000 m, and 4200 m (Desbruyères et al., 2017).

The warming we observed in the West Spitsbergen Current is occurring much faster than the global ocean warming. The temperature in the 0—2000 m layer is increasing at a rate of 0.023°C yr^{-1}, which is equivalent to 5.98 W m^{-2} of heat uptake, almost 6 times more than the mean oceanic heat uptake given by Desbruyères et al. (2017). Of course, this heat was not absorbed from the sun in the studied region and is mainly the effect of ocean heat convergence. However, these data show that the investigated region is a very effective heat sink and that the warming rate is much higher than the mean warming rate for the whole ocean. The intermediate water stores 22% of the heat surplus, and the deep water stores 29%. This confirms that deep and intermediate waters, in addition to surface water, are significant heat sinks. The surplus of heat stored in the West Spitsbergen Current region and transported by the WSC to the Arctic Ocean may have an important influence on Arctic sea ice melting and climate change.

5. Conclusion

In this study, we analyzed potential temperature and salinity increases in intermediate and deep waters in the West Spitsbergen Current region from 1997 to 2016. This area is divided into two parts by the Arctic front (~7°E): the Arctic domain in the west and the Atlantic domain in the east. The increase in the potential temperature of the water was especially intense in the Arctic domain and was associated with considerable changes in the water layers salinity.

The potential temperature and salinity of the intermediate water increased much faster (0.021°C yr^{-1} and 0.0022 yr^{-1}, respectively) than those of the deep water (0.009°C yr^{-1} and 0.0004 yr^{-1}, respectively). The intermediate and deep waters in the study area flow from the central part of the Greenland Sea; therefore, the increases in the temperature and salinity of these waters are related to the changes observed in the central Greenland Sea. This is most clearly observed in the western part of the area (Arctic domain), where the direct water supply from the central Greenland Sea is not inhibited by the Knipovich Ridge, unlike in the eastern part (Atlantic domain).

The increases in salinity and temperature in the intermediate water have also been associated with the advection of anomalously warm and saline Atlantic Water in recent years, which enters the region from the North Atlantic. This has contributed to deeper convection in the Greenland Sea, ventilating the intermediate water and increasing both the temperature and salinity of this layer. The temperature and salinity increases in the intermediate water were more substantial, with considerably higher interannual fluctuations, than the variability in the deep water physical properties. The source of the increases in temperature and salinity in the deep water is the inflow of relatively warm and salty Eurasian Basin Deep Water from the Arctic Ocean to the relatively cold and fresh Greenland Sea Deep Water in the Greenland Sea.

A temperature increase of 0.46°C in the 2000 m water column causes a mean increase in the heat content of 3770 MJ m^{-2} and requires an additional 5.98 W m^{-2} of atmosphere-ocean heat flux per 20 years, almost 6 times more than the mean oceanic heat uptake.

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