Oceanologia (2017) 59, 187—194

Available online at www.sciencedirect.com

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SHORT COMMUNICATION

Oceanographic observations in the Nordic Sea and Fram Strait in 2016 under the IO PAN long-term monitoring program AREX

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Received 13 December 2016; accepted 25 December 2016
Available online 13 January 2017

KEYWORDS
Nordic Seas;
Physical oceanography;
Atlantic water

Summary Since 1987 annual summer cruises to the Nordic Seas and Fram Strait have been conducted by the IO PAN research vessel *Oceania* under the long-term monitoring program AREX. Here we present a short description of measurements and preliminary results obtained during the open ocean part of the AREX 2016 cruise. Spatial distributions of Atlantic water temperature and salinity in 2016 are similar to their long-term mean fields except for warmer recirculation of Atlantic water in the northern Fram Strait. The longest observation record from the section N along 76°30′N reveals a steady increase of Atlantic water salinity, while temperature trend depends strongly on parametrization used to define the Atlantic water layer. However spatially averaged temperature at different depths indicate an increase of Atlantic water temperature in the whole layer from the surface down to 1000 m.
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1. The IO PAN long-term monitoring program AREX

The northernmost polar region is most sensitive to global climate change and its effects are most exaggerated and have the biggest impact in the Arctic. Climate change is faster and more severe in the Arctic, which is warming at a rate of almost twice the global average (Cohen et al., 2014; Serreze et al., 2009). A steady temperature increase, observed both in the atmosphere and in the ocean, has a profound impact on the sea ice cover in the sub-Arctic seas

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Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

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http://dx.doi.org/10.1016/j.oceano.2016.12.003
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and Arctic Ocean (e.g. Polyakov et al., 2012; Stroeve et al., 2012). In the last two decades, the summer sea ice extent has shrunk dramatically together with a strong decline of its thickness and volume (Serreze and Stroeve, 2015). While many complex feedback processes contribute to the enhanced warming of the Arctic region called Arctic amplification, it is largely driven by the loss of the sea ice cover, allowing for strong heat transfers from the ocean to the atmosphere. By exposing larger dark open areas, where the ocean can absorb more of the sun's energy and in consequence warm further, the loss of sea ice in the Arctic Ocean also has the potential to accelerate global warming trends and to change climate patterns (Overland, 2016).

Large oceanic exchanges between the North Atlantic and the Arctic Ocean result in the strong conversion of water masses when warm and salty Atlantic water (AW), transported through the Nordic Seas into the Arctic Ocean, undergo cooling, freezing and melting. As a result, it is transformed into freshened shelf waters over the shallow shelves, sea ice and dense (and highly saline) deep waters (e.g. Dickson et al., 2008). Southward transport of the Arctic origin and dense overflow waters is one of the main mechanisms of the global thermohaline circulation (THC, e.g. Mauritzen, 1996). A better understanding of the variability of volume and heat transports between the North Atlantic and Arctic Ocean as well as processes of water mass conversion is necessary for improved qualitative and quantitative estimation of the large-scale meridional overturning circulation and its role in shaping the climate change in the northern hemisphere on inter-annual to decadal time scales.

Fram Strait is the only deep passage linking the Nordic Seas and the Arctic Ocean. The northward transport of warm and salty Atlantic water, carried by the Norwegian-Atlantic Current and farther by the West Spitsbergen Current, has a significant impact on conversion and circulation of water masses in the Arctic Ocean (e.g. Rudels et al., 2015) as well as on sea ice and atmospheric fluxes in the Arctic. The complex bottom topography of the northern Greenland Sea and Fram Strait results in the splitting of both currents into several branches, located along the underwater ridges and the continental slope (e.g. Bourke et al., 1988; Quadfasel et al., 1987; Walczowski, 2014). The spatial extent and relative intensity of these branches to a great degree determine oceanic heat flux into the Arctic Ocean (e.g. Beszczynska-Möller et al., 2012; Schauer et al., 2008).

Understanding of Arctic climate processes is the main aim of the current oceanographic and atmospheric studies carried on in the polar region. The Institute of Oceanology PAN (IO PAN) contributes to this challenge with the strategic research initiative addressing the role of the ocean in changing climate and its effects on the European seas. Its core activity, the long-term monitoring program AREX, is focused on multidisciplinary observations in areas such as physical oceanography, air—ocean interactions, ocean biogeochemistry and ecology to study the long-term changes of abiotic and biotic Arctic environment. Every summer since 1987 the large-scale field measurements have been carried out in the Nordic Seas and European Arctic from the board of the IO PAN research vessel *Oceania*. These data, collected under the observational program AREX every year in the same way, provide time series of key ocean variables which allow monitoring changes of the Arctic environment and improving numerical simulations of ocean, sea ice and climate in the Arctic region.

The main aim of the long-term AREX program and annual cruises, carried by r/v Oceania for the last 30 years in the Nordic Seas and Fram Strait, is to recognize and describe processes responsible for changing ocean climate and marine ecosystem in the sub-Arctic and Arctic region with a special focus on the European Arctic (Walczowski, 2014). To achieve this goal a large-scale study area, covering the poleward flow of Atlantic water in the eastern Nordic Seas and Fram Strait, has been selected for annually repeated ship-borne measurements on a regular grid. Most of the regularly repeated stations are distributed along several zonal sections, crossing the continental shelf break at the right angle and extending towards the deep basin. On the eastern side, the AREX oceanographic sections are limited by the Barents Sea shelf break and the shelf area west and north of Svalbard. To the west, the sections cross the Arctic Front, located above the system of underwater ridges (the Mohn and Knipovich ridges) and limiting the extent of Atlantic water in the Nordic Seas. The zonal sections following the Atlantic water inflow from the Norwegian Sea to the northern Fram Strait allow to assess transformation of water masses originating from the North Atlantic and advected northward. Two meridional sections, one from the northern Norway towards the Bear Island and one between the Bear Island and the southernmost tip of Svalbard (Sørkapp), cover the eastward flow of Atlantic water to the Barents Sea.

The AREX program and IO PAN field campaigns in the Arctic region are mainly based on statutory funding but since the early 90s they have also contributed significantly to several international projects, e.g. VEINS (Variability of Exchanges in the Nordic Seas, 1997—2000), ASOF-N (Arctic and subArctic Oceanic Fluxes — North, 2003—2005), and IP DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environment Studies, 2006—2009). The summer measurement campaigns of r/v Oceania and year-round observations with oceanographic moorings in the Nordic Seas, Fram Strait and, in recent years, in the southern Nansen Basin also provided crucial data for several projects under the Polish-Norwegian Research Program, including AWAKE-1 and -2, PAVE, CDOM-HEAT, POLNOR, and others. Last but not least, time series of ocean observations, collected in the last 30 years from r/v Oceania, have been employed by many IO PAN researchers and PhD students to carry on numerous studies of the Arctic climate and environment in the frame of IO PAN statutory research.

2. Oceanographic measurements during the AREX 2016 cruise

The AREX cruise of the IO PAN research vessel *Oceania*, repeated every summer over the same time period (June—August), in 2016 took place from June 14 to August 29. Two legs of the AREX 2016 cruise were devoted to the collection of oceanographic, meteorological, aerosol and ocean ecosystem observations in the open ocean regions, including the eastern Norwegian and Greenland seas, Fram Strait and the southern Nansen Basin of the Arctic Ocean.

The hydrographic survey carried out during the AREX 2016 cruise consisted of 11 sections extending from the outer

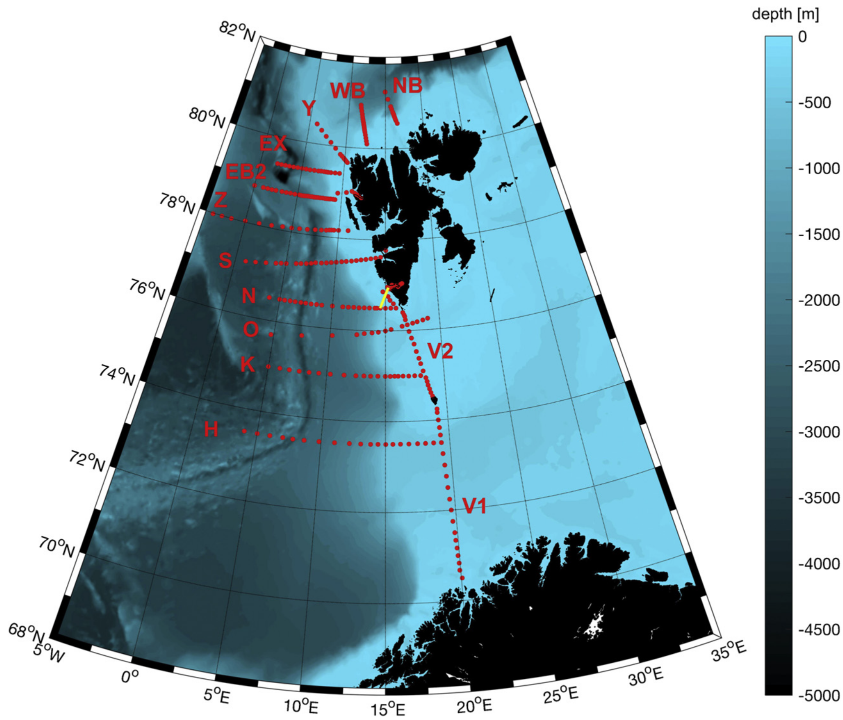

Figure 1 Location of CTD stations measured during the open ocean part of AREX 2016 (June 21—July 24, 2016). Red dots mark CTD stations and yellow line shows the high-resolution towed CTD section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shelf across the slope into the deep basin in order to sample the northward flow of Atlantic water and 2 meridional sections across the Barents Sea Opening and Storfjorden Trough to assess the exchange with the Barents Sea. A total of 270 conductivity-temperature-depth (CTD) full-depth stations within the geographical area 70°30′—81°15′N and 0—20°E (with one section extending to 5°W) were carried out from June 21 to July 24, 2016, on board the r/v *Oceania* (Fig. 1). In addition to CTD casts, the ocean currents were measured with a Lowered Acoustic Doppler Current Profiler (LADCP) at each station and the upper ocean currents were continuously recorded during the whole survey with a Vessel-Mounted Acoustic Doppler Current Profiler (VMADCP). Water samples were collected at selected stations for calibration of conductivity sensor and biological and biogeochemical analyses.

Oceanographic measurements and collection of water samples during the AREX 2016 cruise contributed to several IO PAN statutory tasks and external research projects (national and international). Observations were carried on by three groups of scientists, focused on physical oceanography, meteorology and air—ocean interactions, and marine biology, but collaborating together during different shipborne measurements. A total of 10 scientists were supported on deck by two oceanographic instrumentation technicians and the ship crew for the heavy gear operations (e.g. carousel water sampler, multinet).

Following oceanographic measurements were carried on during the open ocean part of the AREX 2016 cruise:

- Full-depth measurements of temperature, salinity, dissolved oxygen and ocean currents in the Norwegian-Atlantic and West Spitsbergen currents (CTD, LADCP, VMADCP).
- High-resolution hydrographic measurements with a towed CTD system (scan-fish) at the section across the shelf and shelf break west of Svalbard (in the vicinity of the Hornsund outlet).
- A collection of water samples for calibration of conductivity and oxygen sensors and nutrient analysis.
- Deployment of two ARGO floats in the Norwegian Sea.

Additionally, the standard meteorological observations were carried out according to the SHIP standard and instantaneous values of wind components, air humidity and CO_2 concentration were measured separately. Concentration and distribution of marine aerosols, as well as aerosol optical thickness, were measured at selected stations. On selected stations, plankton samples were collected with various sampling gear (WP2 nets, Multiple Plankton Sampler) and preserved for different biological analyses in the laboratory.

The standard CTD system Seabird 9/11+ used during the AREX 2016 cruise was equipped with double pairs of temperature (SBE3) and conductivity (SBE4) sensors and Digiquartz pressure sensor 410K-105. Additionally, CTD system carried two dissolved oxygen sensors (one standard SeaBird sensor SBE43 and additional Rinko optode, connected directly to the CTD registration system), SeaPoint fluorescence sensor and Benthos altimeter Benthos PSA-916. The CTD system was mounted on the SeaBird bathymetric rosette (carousel) equipped with 9 large Nansen bottles (12 l each) and 3 small bottles (1.75 l each). Originally the rosette is designed to carry 12 large bottles but due to the mounting system for LADCP only 9 bottles can be used in the current configuration. RDI Teledyne Workhorse 300 kHz was used as Lowered Acoustical Doppler Profiler (LADCP), mounted in downward-looking configuration. The collected CTD data were registered on the

PC hard drive with a double backup on the external RAID array. The preliminary data processing was done in the near-real time while the final data set was available after the post-cruise calibration of sensors. The LADCP data were read out after each station and stored in single files for each cast. During the entire cruise, the underway measurements of ocean currents in the upper layer of about 300 m depth were continuously recorded with the Vessel Mounted Acoustic Doppler Current Profiler (RDI VM-ADCP 150 Hz).

3. Properties of Atlantic water in summer 2016 and their long-term variability

Since 2000, oceanographic measurements during the open ocean part of r/v *Oceania* cruise under the AREX program have been collected at the same stations, almost on the same day of the year. Collected time series of water properties are used to study long-term changes in the ocean climate in the

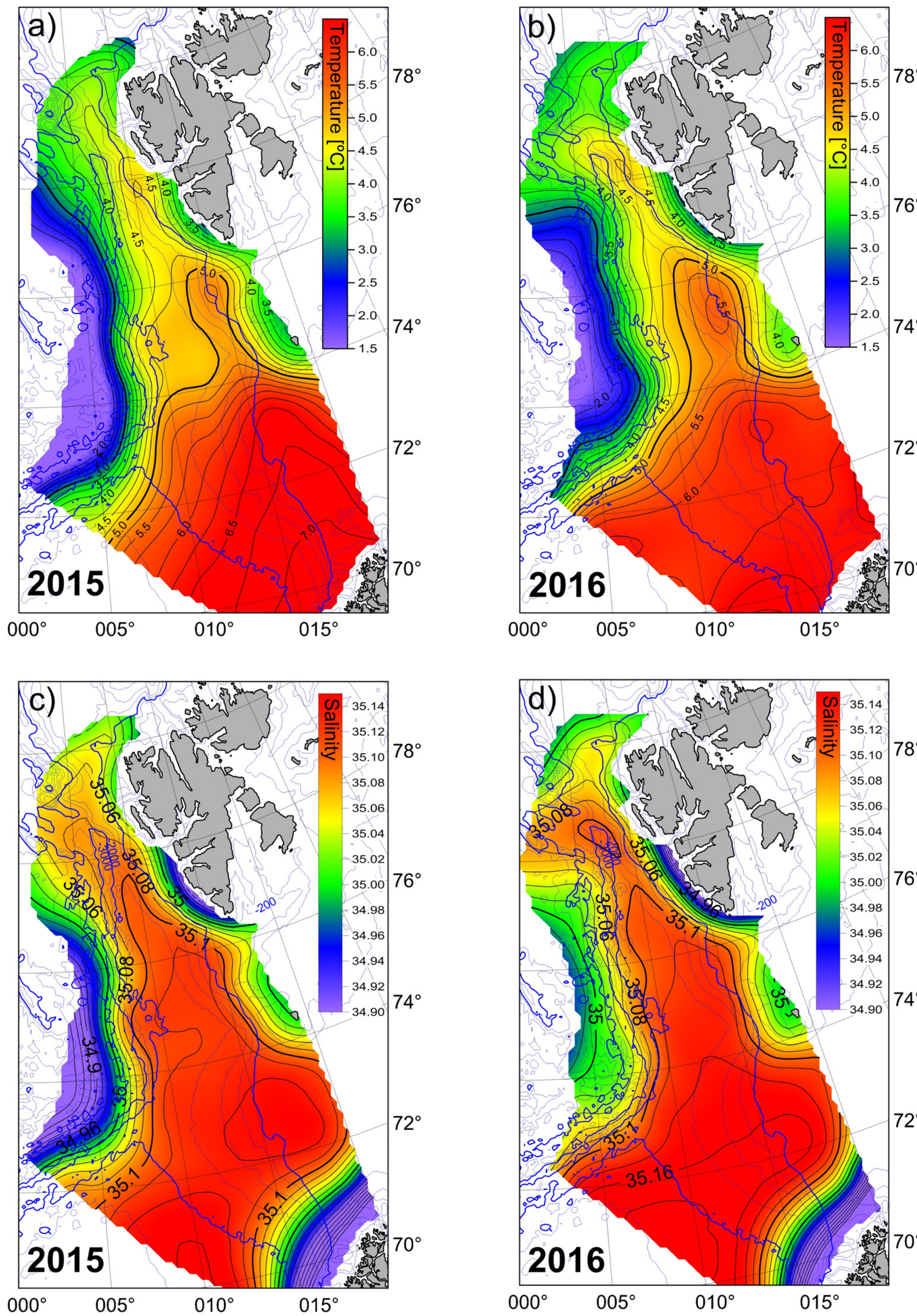

Figure 2 Spatial distribution of temperature measured in (a) 2015 and (b) 2016, and salinity measured in (c) 2015 and (d) 2016 at the depth of 100 m. Thick lines depict isotherms 5°C and 0°C (a and b) or isohalines 35.0 and 35.1 (c and d). Norwegian data from the Gimsøy section were used to extend the studied area towards the southwest.

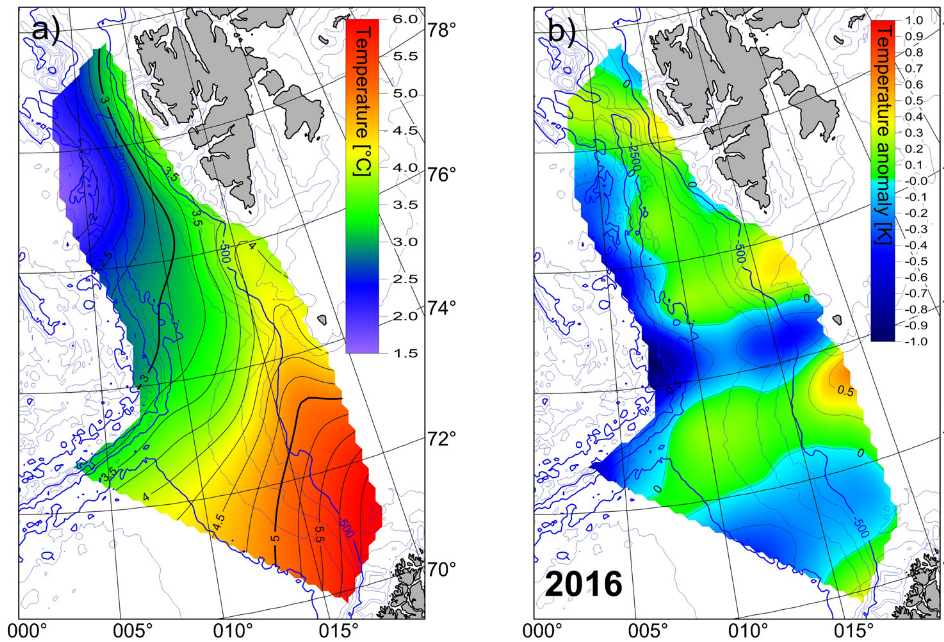

Figure 3 (a) The long-term mean field (2000—2016) of vertically averaged temperature in the Atlantic water layer and (b) anomaly of vertically averaged AW temperature measured in summer 2016 during the open ocean part of AREX 2016.

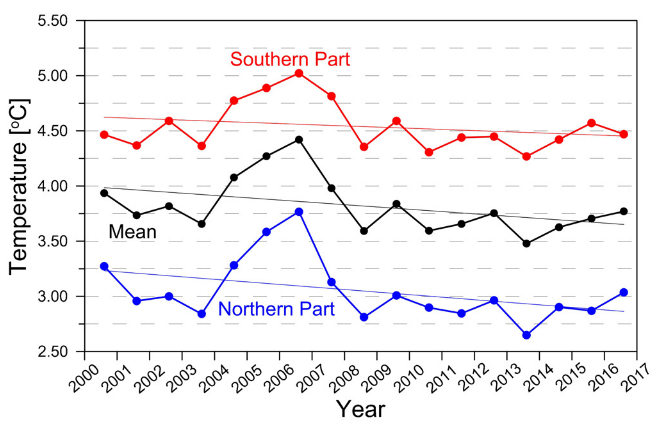

Figure 4 Vertically and spatially averaged temperature of the Atlantic water layer in the studied area. The black line depicts mean values for the whole area, the red line for the southern part (south of 74°N) and the blue line for the northern part (north of 74°N). Atlantic water is defined as warmer than 0°C and more saline than 34.92 (Walczowski, 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

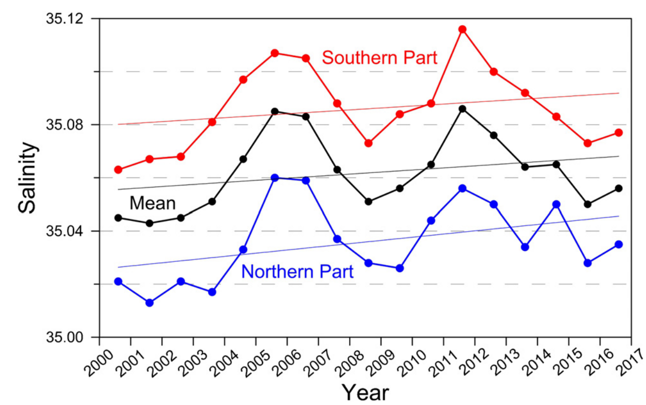

Figure 5 Vertically and spatially averaged salinity of the Atlantic water layer in the studied area. The black line depicts mean values for the whole area, the red line for the southern part (south of 74°N) and the blue line for the northern part (north of 74°N). Atlantic water is defined as warmer than 0°C and more saline than 34.92 (Walczowski, 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1 Vertically averaged temperature (*T*) and salinity (*S*) in the Atlantic water layer, calculated for the whole studied area (T_whole and S_whole) and separately for its northern (T_northern and S_northern) and southern (T_southern and S_ southern) parts.

Parameter	Long-term mean (LTM), 2000—2016	STD, 2000—2016	2015	2016	Difference, 2016—2015	Difference, 2016—LTM
T_whole	3.82	0.25	3.71	3.77	0.06	−0.05
S_whole	35.06	0.01	35.05	35.06	0.01	0.00
T_southern	4.36	0.22	4.57	4.47	−0.10	0.11
S_southern	35.09	0.02	35.07	35.08	0.01	−0.01
T_northern	3.05	0.29	2.87	3.04	0.17	−0.01
S_northern	35.04	0.02	35.03	35.04	0.01	0.00

Nordic Seas and Fram Strait. The AREX 2016 cruise extended all time series to 17 years. However, the longest time series collected at the section N along 76°30′N started already in 1996 and covers 21 years of summer observations. Due to its length, this time series is used as representative for temporal variability of the Atlantic water properties. Methods of calculating the spatially averaged properties of Atlantic water are presented in detail by Walczowski (2014).

Oceanographic conditions observed in summer 2016 in the studied region were close to the long-term mean situation. Similar as in 2015, the meridional extent of water warmer than 5°C observed at the depth of 100 m slightly exceeded the latitude of 76°N (Fig. 2a and b). The Arctic Front, depicted by the isotherm 3°C, was located at the same position as in 2015. Only in the northern Fram Strait, the westward deflection of isotherms can indicate stronger

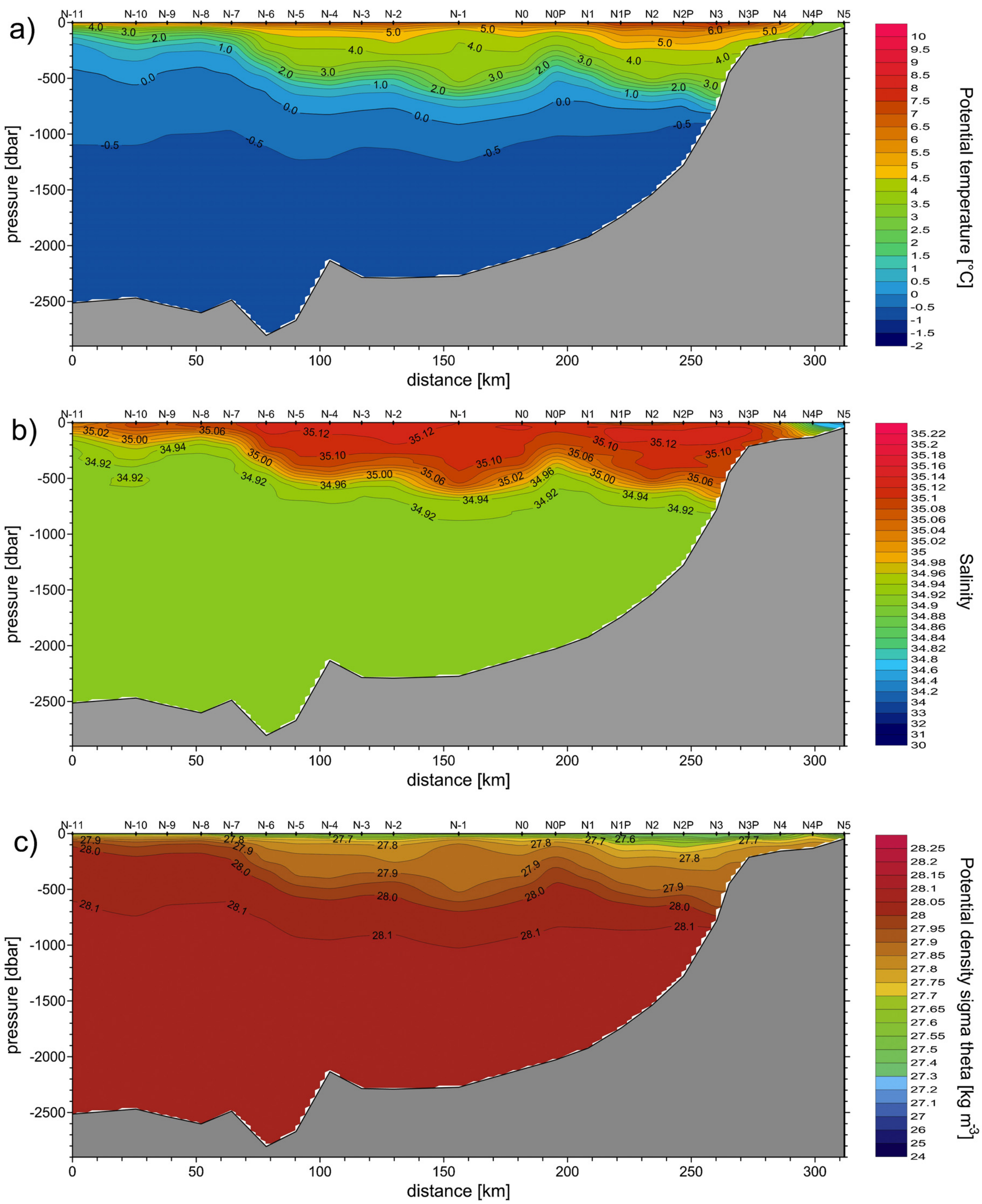

Figure 6 Vertical distributions of (a) potential temperature, (b) salinity and (c) potential density at the section N along 76°30′N observed in summer 2016.

westward recirculation of Atlantic water in 2016, concurrent with the weaker flow in the West Spitsbergen Current towards the Arctic Ocean. Spatial distribution of salinity at the depth of 100 m was also similar in 2015 and 2016 in the studied area (Fig. 2c and d).

The long-term mean field (2000—2016) of vertically averaged temperature in the Atlantic water layer is shown in Fig. 3a. Anomalies of vertically averaged AW temperature, presented in Fig. 3b, reveal slightly positive signal close to the Barents Sea Opening and in the eastern Fram Strait.

Time series of the vertically averaged temperature and salinity in the Atlantic water layer (defined as water with $T > 0$°C and $S > 34.92$), calculated for the whole studied area and separately for its northern and southern parts confirm, that AW temperature and salinity observed in summer 2016 were close to their climatological mean values (Fig. 4 and Table 1). Anomalies of mean AW temperature and salinity in 2016, calculated with respect to the long-term mean 2000—2016, were all below their standard deviations. Mean AW temperature and salinity for the northern part of the studied area (north of the Bear Island) were 3.04°C and 35.04 in 2016 as compared to their values observed in 2015 (2.97°C and 35.04, respectively). Mean AW temperature calculated for the whole studied region in 2016 was higher than in 2015, mostly due to higher AW temperatures in its northern part. In the southern part of the measured area mean AW temperature in 2016 was lower than in 2015 but still higher than its climatological mean 2000—2016 (Table 1). Mean AW salinity reached the maximum in 2011 and since then a steady decrease has been observed until 2015. In 2016 a small increase of AW salinity was observed in the whole studied area (Fig. 5).

Temperature and salinity distribution at the section N along 76°30′N (Fig. 6) were also close to their long-term means. The eastern branch of the West Spitsbergen Current (the WSC core) is clearly visible between 12 and 14°30′E (between stations N1 and N4P). On the eastern side the hydrographic front is visible on the shelf, separating warm Atlantic water carried by the West Spitsbergen Current from cold and freshened waters of the Sørkapp Current. To the west of the West Spitsbergen Current, the westward extent of Atlantic water is limited by the Arctic Front located about 7°E (station N-6). Farther westward the recirculating Atlantic water towards the Greenland Sea can be traced in the upper layer.

The longest observed time series of Atlantic water temperature and salinity, measured since 1996 at the section N along 76°30′N are shown in Fig. 7. The Atlantic water layer was defined with $T > 0$°C and $S > 34.92$ and mean values were calculated only for the part of the section limited to the west by 6°33′E to exclude the recirculating Atlantic water. A slight increase of AW mean temperature and salinity was found for 2016 as compared to 2015. Mean AW temperature at the section N was 2.96°C in 2016 and exceed the 2015 value by 0.13°C. Mean AW salinity of 35.04 observed in 2016 was higher by 0.03 than measured in 2015. The long-term trends of AW temperature and salinity are both positive for the period 1996—2016.

Since a definition of the Atlantic water layer is based on temperature and salinity (or density) criteria, it strongly influences the temporal variability of AW mean temperature and salinity, calculated according to different parametrizations. Therefore mean temperature in the central part of section N (limited by 9°N and 12°N, laying between 130 and 210 km) was also calculated for selected depth levels (Fig. 8). The maximum temperature is visible between 2004 and 2006 depending on the depth level. The temperature trend reaches 0.058°C year^{-1} in the upper layer between 0 and 400 m and decreases with depth to 0.015°C year^{-1} observed at the depth of 1000 m. Temperature trends are positive and statistically significant (with p-values less than 0.01) for all depth levels. Observed trends at the section N confirm positive temperature trend observed overall in the eastern Nordic Sea and accompanied by positive salinity trend (Larsen et al., 2016).

While the 21-year-long time series of observations captures significant changes in water mass properties, it is still too short to separate the effect of trends caused by the ongoing climate change from multidecadal variability. The Atlantic meridional thermohaline circulation and associated fluctuations of poleward oceanic fluxes are strongly linked to the Atlantic Multidecadal Oscillation, which has been identified as a coherent mode of natural variability with an estimated period of 60—80 years (Delworth and Mann, 2000). Those multidecadal changes have been recently supported with strong observational evidence (e.g. McCarthy et al., 2015; O'Reilly et al., 2016). In-depth discussion of observed changes in relation to large-scale variability is out of the scope of this short communication and will be addressed in a separate paper.

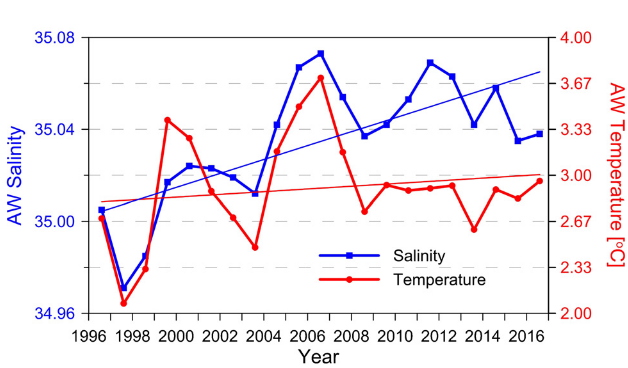

Figure 7 Time series of the vertically averaged temperature and salinity of the Atlantic water layer at the section N along 76°30′N measured in summers of 1996—2016.

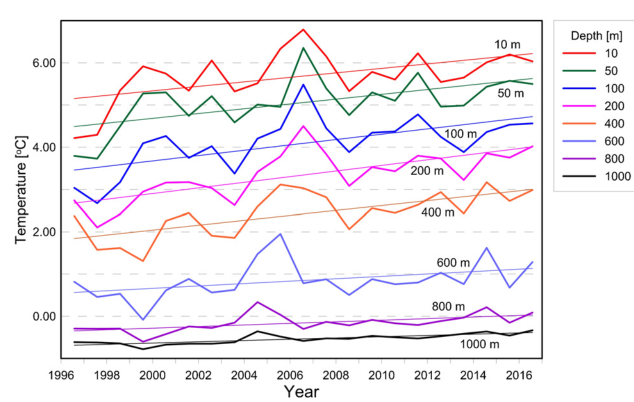

Figure 8 Time series of temperature at the selected depths observed in the central part of the section N (between 9 and 12°E, i.e. between 130 and 210 km of the section).

Oceanographic data collected under the AREX long-term monitoring program during the 30th cruise of r/v *Oceania* were used to extend time series of Atlantic water properties and analyze long-term changes observed along the Atlantic water inflow in the Nordic Seas and Fram Strait towards the Arctic Ocean. Based on the results of a preliminary analysis, summer hydrographic conditions observed in the Atlantic water domain in 2016 were close to their long-term averages. Atlantic water salinity reveals a clear positive trend while its temperature trend depends strongly on used definition of the Atlantic water layer. However spatially averaged temperature at different depths, calculated for the longest time series, indicates a clear increase of Atlantic water temperature in the whole layer from the surface down to 1000 m.

Acknowledgements

The 2016 field campaign of r/v *Oceania* in the Nordic Seas and Fram Strait was carried out under the IO PAN long-term program AREX and contributed to the IO PAN statutory research areas I.3, I.4 and I.5 and to activities of the Center for Polar Studies. The fieldwork was also supported by the projects PAVE and AWAKE-2 under the Polish-Norwegian Research Program. CTD data from the Gimsøy section were kindly provided by Kjell-Arne Mork from the Institute of Marine Research in Bergen. The captain and crew of r/v *Oceania* are gratefully acknowledged for extensive help and support provided over many years during the challenging field measurements in the harsh Arctic conditions.

Appendix A. Supplementary data

Supplementary data associated with this article (a station list, a cruise itinerary) can be found, in the online version, at doi:10.1016/j.oceano.2016.12.003.

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