



## Changes in Atlantic water properties: an important factor in the European Arctic marine climate

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The advection of warm Atlantic water (AW) through the Nordic Seas and its transformation (cooling and freshening) is one of the most important climatological processes in the region. Time-series of hydrographic observations in the northern Nordic Seas and the Fram Strait region are presented and analysed. Significant variability in the properties of AW has been observed in recent years. A 15-year time-series of summer observations indicate positive trends in salinity and temperature and two 5–6-year cycles. The northward advance of AW in 2006 was an unprecedented event. The position of the warm-water tongue shifted more than 350 km to the north, and temperatures in the West Spitsbergen Current reached the highest values ever recorded. These changes in AW temperature, heat content, and northward transport had a strong influence on the oceanic climate and sea-ice conditions north of Svalbard. These oceanic signals led to environmental changes that confirm the primary role of the ocean in shaping the climate of the region.

**Keywords:** Atlantic water, climate, interannual variability, Nordic Seas, ocean currents.

### Introduction

Two-way oceanic exchanges connecting the Atlantic and Arctic Oceans are of basic importance to the global climate (Dickson *et al.*, 2008; Rhines *et al.*, 2008). The inflow of waters of Atlantic origin (Atlantic water, AW) into the Nordic Seas, their cooling and freshening, recirculation, and convection, on their way towards the Fram Strait, are of basic importance to the global thermohaline circulation and to heat and freshwater fluxes at the ocean surface (Van Aken, 2006). The ice-free region between the Barents Sea shelf and the Knipovich Ridge is the area where ocean–atmosphere heat and buoyancy fluxes are the highest (Isachsen *et al.*, 2007). The densification of AW in the Nordic Seas, especially west of Svalbard, is very significant for dense-water formation and the forcing of the Atlantic Meridional Overturning Circulation. In addition, AW is the main source of heat and salt for the Arctic Ocean.

There are three separate branches of AW inflow into the Nordic Seas (Figure 1), all of which are extensions of the North Atlantic Current. The North Icelandic Irminger Current (NIIC) flows into the Iceland Sea through the Denmark Strait. The major part of AW volume is transported into the Nordic Seas by the Faroe Current (Faroe Branch) and the Continental Shelf Current (Shetland Branch). The continuations of these currents, the two branches of the Norwegian Atlantic Current (NwAC), carry AW

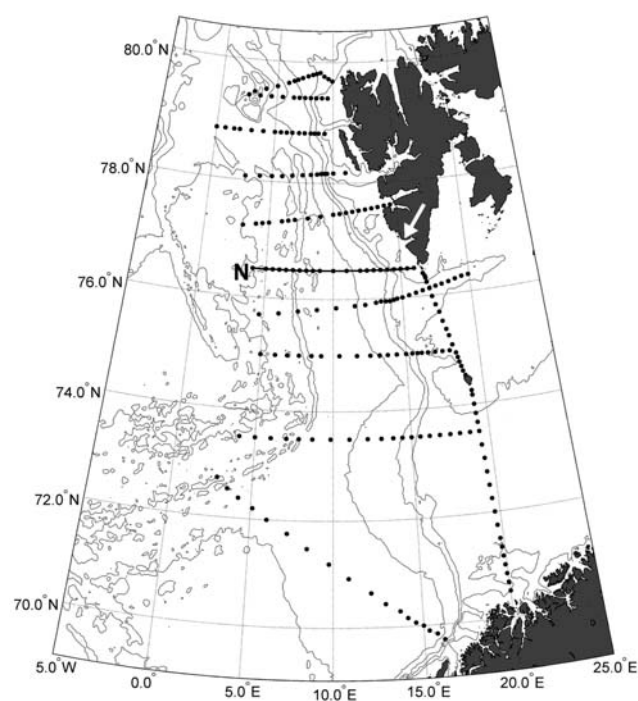
through the Norwegian Sea (Orvik and Niiler, 2002). The eastern flow, also known as the Norwegian Atlantic Slope Current (NwASC), divides after passing Norway: one part flows east into the Barents Sea and the other continues north to the Fram Strait as the core of the West Spitsbergen Current (WSC). The NwAC continues over the Mohn and Knipovich Ridges, forming the western branch of the WSC. The bottom topography of the Fram Strait region forces both branches to converge there, and then to diverge again.

### Data and methods

The Institute of Oceanology, Polish Academy of Sciences (IOPAN), has been investigating the northern part of the AW flow into the Arctic Ocean, the WSC, since 1987. Every summer, the IOPAN research vessel “Oceania” operates in the region between northern Norway and the Fram Strait. To reduce the influence of seasonal variability on the results, measurements are always performed at the same time of year: RV “Oceania” starts from Tromsø (Norway) on 20 June and finishes its cruise in Longyearbyen (Spitsbergen) on 20 July. During that time, vertical profiles along standard sections (Figure 2) are obtained. The sections are perpendicular to the general direction of AW flow, in accord with the WSC’s location, which is between the Barents Sea slope in the southeast, the west



**Figure 1.** A schematic illustration of AW inflow into the Nordic Seas.



**Figure 2.** The grid of stations occupied by RV "Oceania" every summer. The 200, 500, 1000, 2000, 3000, and 4000 m isobaths are drawn as contours. The location of section N (line) and the Polish Polar Station in Hornsund (arrow) are indicated.

Spitsbergen shelf break/slope region in the northeast, and the underwater ridge system of the Mohn and Knipovich ridges in the west. Currents are mostly steered by the bottom topography; because of the convergence of isobaths in the northern part, the pattern and structure of the currents is complicated and forms a wedge, wide in the southern part and narrower in the north. IOPAN's main efforts focus on the northern part of that Atlantic Domain, where processes controlling AW inflow into the Arctic Ocean through the Fram Strait and westward recirculation take place.

The Sea-Bird CTD (SBE911+) system with duplicate temperature and conductivity sensors (temperature sensors SBE3, conductivity sensors SBE4, SBE50 digital oceanographic pressure

sensor, and SBE43 dissolved oxygen sensor and fluorometer) was used. Temperature and conductivity sensors were calibrated by the Sea-Bird Electronics service. For the years 2005–2009, CTD data from the Norwegian Gimsøy Section, provided by the Institute of Marine Research, Bergen, were also used.

To obtain comparable statistical results, data from the common region covered by the measurements in summers of 2000–2009 were used. Mean AW properties were calculated from gridded fields. Data were interpolated using optimal interpolation methods, kriging procedures (Emery and Thomson, 2001). Additionally, the rectangular grids were smoothed with a linear convolution low-pass filter. The investigated region was divided by the 74°N parallel into two almost equal northern and southern parts. Baroclinic currents were calculated about the level of no motion at 1000 dB. This layer is situated below the high vertical property gradients and the deepest AW level. The current vectors indicate only the baroclinic component of the flow, but offer a good representation of the general pattern of the flow (Walczowski *et al.*, 2005). The heat content was calculated with respect to a temperature of  $-0.1^{\circ}\text{C}$ .

AW was defined as water warmer than  $0^{\circ}\text{C}$  and more saline than 34.92. In practice, in the majority of casts, both the upper and lower limits of the water column analysed were determined by salinity, and the mean properties of the AW layer were calculated for the water column satisfying the condition  $S \geq 34.92$ . Salinity in the region investigated is more conservative than temperature, so this definition of AW guarantees that the same water mass in the northern and southern parts of the research area is analysed. The  $T = 0^{\circ}\text{C}$  isotherm is usually situated 50–80 m below isohaline 34.92, and the rate of AW cooling during its northward advection does not affect calculations of AW volume. On the other hand, spatial and temporal changes in the  $T$ – $S$  relationships may influence the computation of mean AW temperature and the heat stored in the AW layer. Fortunately, however, this influence is minimal because the mean temperature of AW for salinity 34.92 oscillates around  $0.5^{\circ}\text{C}$ .

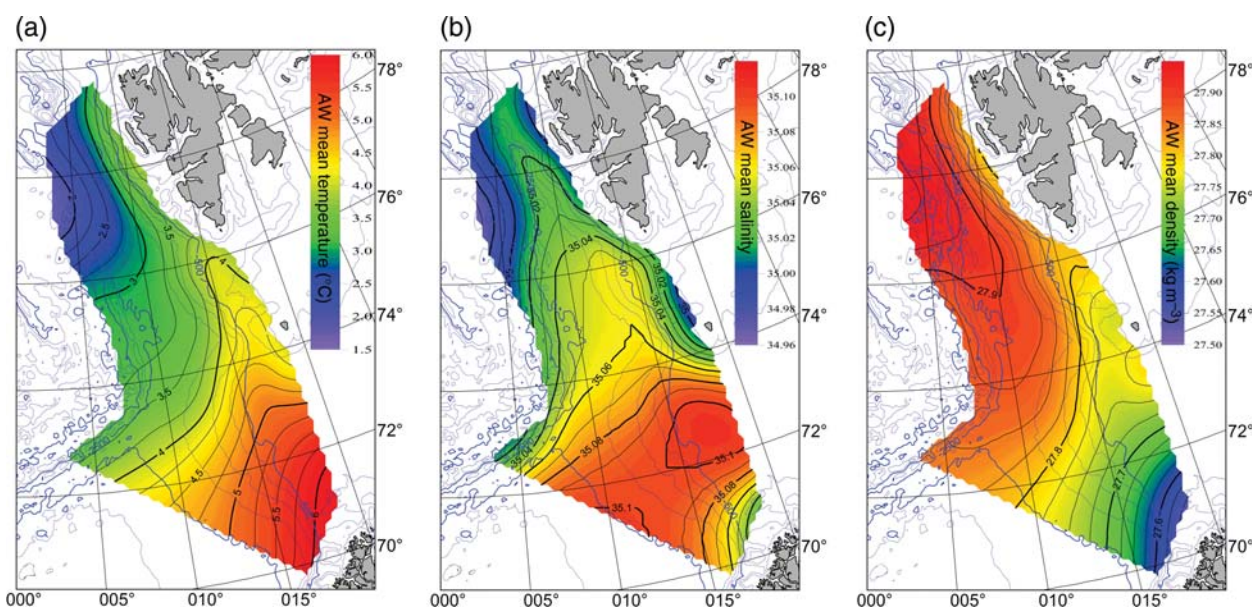
A time-series from the section along  $76^{\circ}30'\text{N}$  is presented. This is the longest time-series used here and covers summers of 1996–2010.

## 2000–2010 summer mean of AW properties

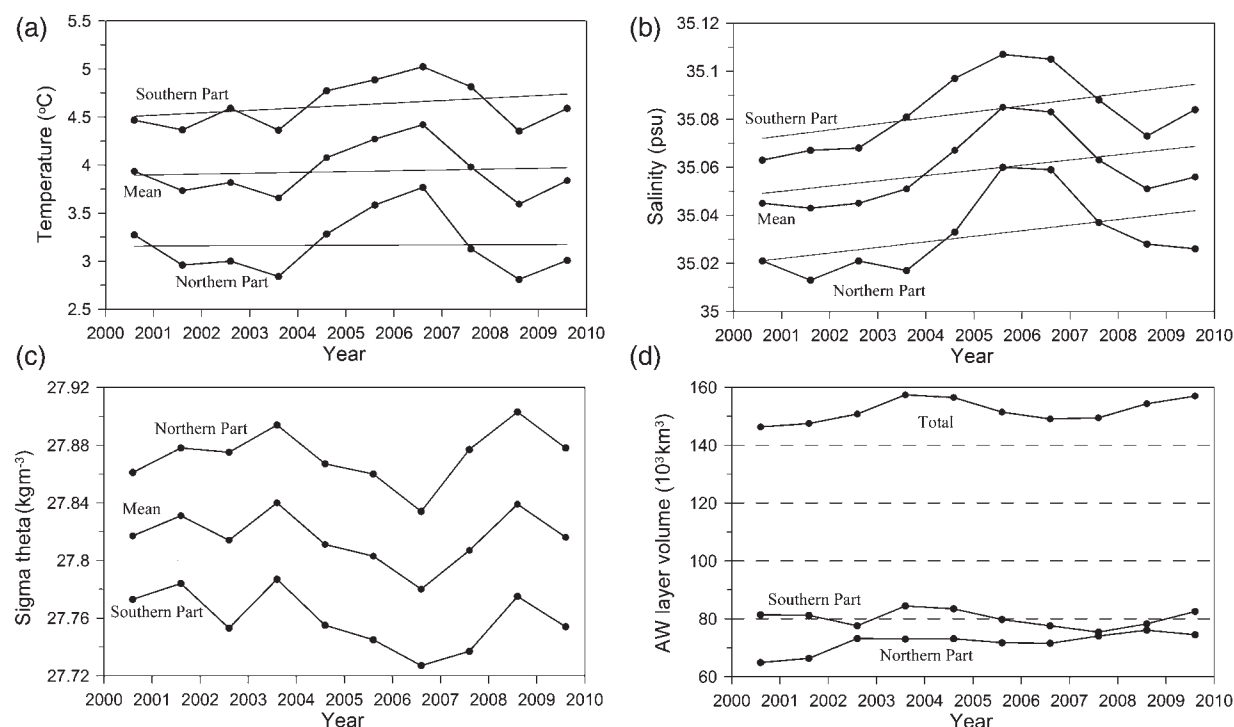
The spatial distributions of the mean temperature and salinity of the AW layer (Figure 3) characterize the water's transformation during its northward flow. In the southern part, the water is warmer and more saline, with mean AW temperature and salinity of  $5.5^{\circ}\text{C}$  and 35.1, respectively, compared with the corresponding values of  $2.5^{\circ}\text{C}$  and 35.01 in the north. The water density also changes significantly, with the strong densification of the AW column, from  $27.7 \text{ kg m}^{-3}$  in the Barents Sea Opening to  $27.92 \text{ kg m}^{-3}$  in the Fram Strait. The negative buoyancy flux is maintained mainly by water cooling and heat fluxes to the atmosphere. Freshening of AW provides positive buoyancy, but the freshwater input does not compensate densification because of the cooling. The density and temperature patterns are therefore similar, but changes have opposite signs.

The salinity field clearly shows two main directions of AW flow: eastwards to the Barents Sea and northwards to the Fram Strait region. The core of the warm northward flow is situated on the eastern side, over the Barents Sea/Svalbard shelf break.

Significant variability in AW mean properties was observed in the period 2000–2009. The highest AW temperature was recorded



**Figure 3.** Maps of 2000–2009 summer mean (a) temperature, (b) salinity, and (c) potential density of AW.



**Figure 4.** Time-series of summer (a) temperature, (b) salinity, (c) density, and (d) volume of AW in the area investigated, indicating mean values for the entire area, the northern part (north of 74°N) and the southern part. Linear trends of temperature and salinity are also shown.

in summer 2006 (Figure 4a), and the maximum AW salinity in 2005 (Figure 4b). The increase in both properties began in 2004 and ended in 2006. During the years 2000–2009, there were positive linear trends in both temperature and salinity. For the entire area, the temperature trend was  $0.009^{\circ}\text{C year}^{-1}$  and the salinity trend was  $0.0022 \text{ year}^{-1}$ . In addition, the mean AW density (Figure 4c) and volume of AW (Figure 4d) changed significantly

in this period. The AW density was the lowest in the warmest summer of 2006, because density changes were influenced mainly by changes in temperature and to a lesser extent by salinity. For the same area, the AW volume in the northern part was less than in the southern part; in the northern part, the AW layer was simply thinner. The changes in AW volume in the northern part were negatively correlated with changes in the south. The



highest correlation coefficient ( $-0.5$ ) occurred for a 1-year time-lag, the changes beginning upstream, in the southern part. The highest AW volume,  $157\,431\text{ km}^3$  (Figure 4d), was recorded in the coldest year (2003). This gave a mean AW thickness of 501 m (classified as warmer than  $0^\circ\text{C}$  and more saline than 34.92). The volume of AW was least ( $149\,068\text{ km}^3$ ; mean thickness 475 m) in the warmest year (2006). Considering that the heat content was the highest in 2006, the warmest year, a decrease in AW volume is clearly compensated for by an increase in temperature.

### Changes in AW horizontal distribution and current pattern: the 2006 warming

Substantial changes in the AW horizontal distribution and current pattern were observed in the period 2000–2009 as well. During the colder years, like 2003, the northernmost extension of the  $5^\circ\text{C}$  isotherm at the 100 dB level crossed the  $76^\circ\text{N}$  parallel (Figure 5a). The baroclinic currents were directed mostly to the east and transported AW through the Barents Sea Opening to the Barents Sea. During the warmest summer of 2006, the  $5^\circ\text{C}$  isotherm at 100 dB reached the Fram Strait: the broad, warm tongue of AW shifted by more than 350 km northwards. The calculated baroclinic currents were mostly directed northwards and were more intensive. Baroclinic volume and heat transport to the Barents Sea were much lower (Walcowski and Piechura, 2011). After the 2006 warming, the AW tongue retreated and the mean properties of AW reached a minimum in 2008. The 5-year “cycle” was closed.

The Atlantic domain in cold (2003) and “mean” (2009) years was wedge-shaped, with a narrow northern part. In 2006, the northern part of the Atlantic domain was wider and the flow of AW much more intensive.

IOPAN investigations show that the 2006 Fram Strait warming was caused mostly by this amplification of the AW flow (Walcowski and Piechura, 2007). Because the currents were more intensive, the AW residence time in the region was shorter, which limited ocean–atmosphere heat exchange and allowed warmer water to penetrate northwards. On the other hand, the warmer water was less dense (Figure 4c), which could have

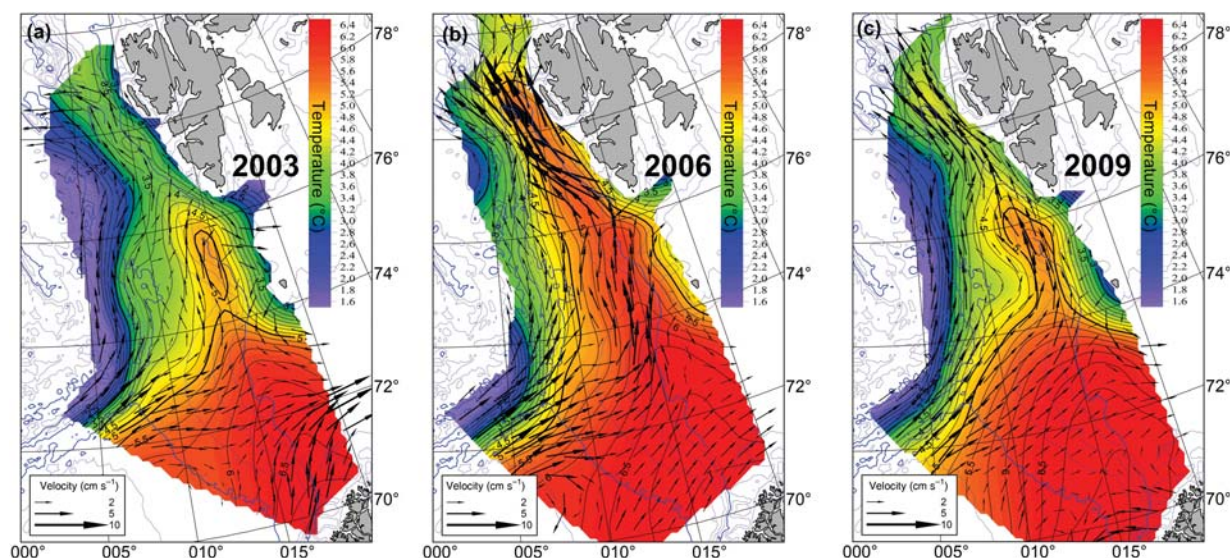
increased baroclinic forcing. This type of positive feedback may have promoted the 2006 warming. The velocities, volume, and heat transport of baroclinic currents change simultaneously with AW temperature changes (Walcowski and Piechura, 2011). For summers of 2000–2009, the correlation coefficient between the mean AW temperature and the mean baroclinic current velocities at 100 dB was 0.76.

Another important aspect of the warming was the intensification of the WSC’s western branch. In 2005, large ( $>150\text{ km}$  in diameter) anticyclonic eddies carrying large heat anomalies were observed in the outer part of the AW flow (Walcowski and Piechura, 2006). Such anomalies were recorded in the Fram Strait in 2006 too. The eddies were much bigger than the usual frontal vortices, and their origin is unknown. They may have advected from the Lofoten Basin, which is the major heat reservoir for the Nordic Seas and has a high eddy activity (Rossby *et al.*, 2009; Koszalka *et al.*, 2011). The  $3^\circ\text{C}$  isotherm observed in the western branch eddies reached a depth of 650 m, comparable with the eddies reported from the Lofoten Basin (Rossby *et al.*, 2009). Moreover, the sizes and anticyclonic direction of rotation of the vortices usually observed in the Lofoten Basin (Gascard and Mork, 2008) and in the western WSC branch in 2006 were similar.

### Section N: AW properties, $\theta$ – $S$ diagrams, $T$ – $S$ correlation, and time-series

The results obtained from the longest IOPAN time-series, at section N along latitude  $76^\circ30'\text{N}$ , give a good description of the changes in AW properties in the region of interest (Schlichtholz and Goszczko, 2006). There is good correlation between the properties of AW at section N and the mean properties in the northern part (Walcowski, 2009). The results can therefore be regarded as representative of the properties of AW in the Fram Strait region. Additionally, as the section is located close to the Polish Polar Station in Hornsund (Figure 1), meteorological observations from this station were used to compare mean air and AW temperatures.

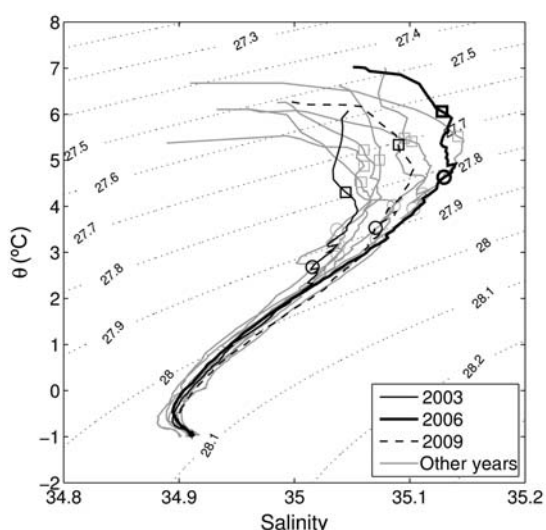
Temperature–salinity ( $\theta$ – $S$ ) diagrams at section N (Figure 6) show the summer-to-summer variability in the water masses in



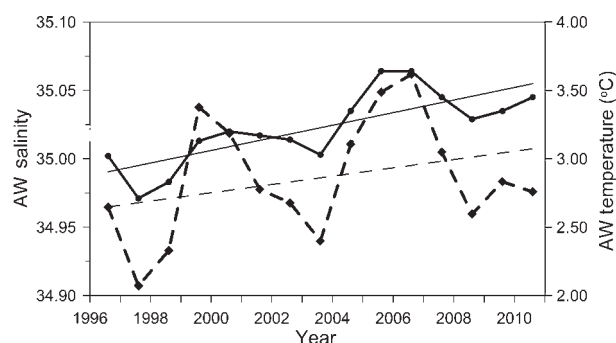
**Figure 5.** Temperature and baroclinic currents at 100 dB in (a) 2003, (b) 2006, and (c) 2009, with a reference level of 1000 dB. The  $5^\circ\text{C}$  isotherm is shown emboldened.

the WSC. Each profile contains stations situated in the core of the current over the continental slope as well as some situated west of the core. Warm years are indicated by a higher salinity maximum, which is generally placed in the subsurface layer but could even form a thick layer, as in 2006. In the cold summer of 2003, the whole AW layer was denser than the mean because of cooling. In the warm summer of 2006, the whole AW column was less dense than the mean. Changes in density are clearly visible in the upper layer of AW and are strongly connected with surface cooling/warming.

The 15-year-long time-series of summer observations indicates two cycles of duration 5–6 years. Both the salinity and the temperature of AW show positive trends. Temperature maxima were in 1999 and 2006 (Figure 7). After 2006, the AW temperature and salinity decreased rapidly. The increase in both properties in 2009 suggested that a new cycle had begun, but in 2010 the AW water cooled again. Simultaneously, the salinity increased, which is a rare phenomenon, for usually there is a positive correlation between AW salinity and temperature. If these phenomena did not occur upstream, then



**Figure 6.** Temperature–salinity ( $\theta$ – $S$ ) diagram for water masses along section N ( $76^{\circ}30'N$ ) during summers of 2000–2009. CTD profiles are averaged between  $07^{\circ}00'$  and  $14^{\circ}25'E$ . Density ( $\sigma_{\theta}$ ) isolines are drawn with a step of  $0.1 \text{ kg m}^{-3}$ . The squares and circles show pressure levels of 50 and 200 dB, respectively. Three profiles indicate cold (2003, solid black line), approximately mean (2009, dashed line), and warm (2006, bold black line) situations.



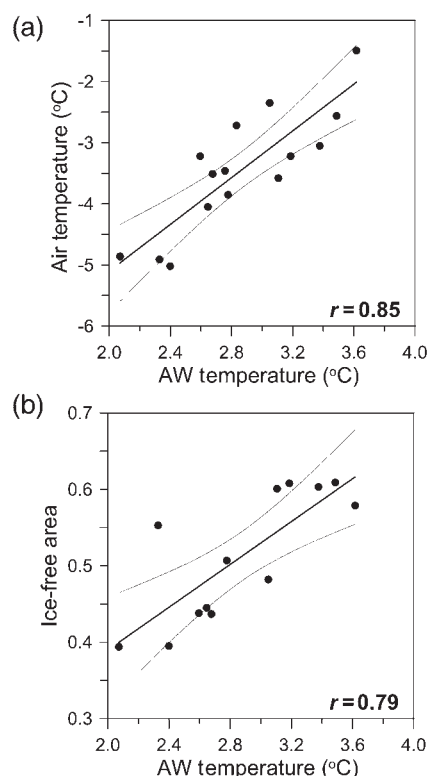
**Figure 7.** Mean temperature (dashed line) and salinity of AW at section N along  $76^{\circ}30'N$  parallel. Linear trends are marked.

presumably in winter 2009/2010 strong ocean–atmosphere heat exchange prevailed over advective oceanic heat transport, thereby strongly modifying AW temperature.

### Influence of AW on the atmosphere and sea ice

There are two causes of the changes in AW properties in the Nordic Seas. Water advected from the south carries seasonal and interannual signals. Additionally, AW is strongly modified in the Nordic Seas. AW mixes with ambient, colder, less-saline waters and exchanges moisture and heat with the atmosphere. In summer, short-wave radiation warms the mixed layer, whereas in winter, the oceanic heat accumulated in the water column and advected from the south is released to the atmosphere. These heat fluxes are very important for the local and global climate. Changes in AW properties and the amount of stored heat affect the hydrosphere, atmosphere, cryosphere, and ultimately the biosphere. There is a good correlation between the temperature of AW section N and the yearly mean air temperature measured at the Polish Polar Station in Hornsund (Figure 8). In summer, the correlation between the AW temperature and air temperature is very weak, if it exists at all, but in winter it rises (Walczowski and Piechura, 2011). The AW temperature signal leads changes in the winter air temperature. This indicates that oceanic heat release is the main mechanism warming the atmosphere there.

There is also a good correlation between the AW temperature and ice conditions north of Svalbard in winter (Piechura and Walczowski, 2009; Schlichtholz, 2011). In this case, too, the AW signal gives rise to changes in ice conditions.



**Figure 8.** Linear regression of mean temperature of AW at section N and (a) the Hornsund yearly mean air temperature and (b) the ice-free area north of Svalbard in the subsequent winter. The 95% confidence levels are marked.

## Conclusions

Positive trends in AW mean temperature and salinity in the WSC region were recorded in summers of 2000–2009. For a longer period, higher values of trends were noted, e.g. in summers of 1996–2010, the mean AW temperature trend at the 76°30'N section (Figure 7) was 0.03°C year<sup>-1</sup> and the salinity trend 0.0046 year<sup>-1</sup>. During that time, there were two periods of warming and cooling. The 2006 warming was the highest ever recorded. Recent publications (Spielhagen *et al.*, 2011) suggest that the AW observed west of Spitsbergen at the start of the 21st century may have been the warmest in the past 2000 years. Therefore, referring to the 2006 warming as an unprecedented event seems justified. The warming was caused mainly by the greater than usual northward transport of AW in the core of the WSC and the large heat anomalies moving along the western branch of this current. Upstream changes in AW temperature (Hughes and Holliday, 2007) probably also favoured this event.

The AW warming, especially that of 2006, caused a change in the ocean climate. Changes in the plankton community structure occurred in the European Arctic: Arctic plankton was displaced by the less energetic Atlantic plankton (Falk-Petersen *et al.*, 2007), which led to transformation of the foodweb. The changes affected fish too. After 2007, cod were sighted and caught in the western fjords of Svalbard and even north of Svalbard (Wassmann *et al.*, 2011); these observations are similar to those made earlier in other polar regions (Jónsson and Valdimarsson, 2005).

After 2006, the temperature and salinity of AW decreased rapidly. It is difficult to predict whether events similar to those of 2006 are possible in the years to come. Nevertheless, the temperature of AW is rising continuously, and this is changing the environment of northern regions.

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