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Influence of the West Spitsbergen Current on the local climate

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ABSTRACT: Oceanographic observations of the Nordic Seas show significant interannual variability of the inflowing Atlantic Water properties and currents structure. Variations of the oceanic heat advected northward with the Atlantic Water influence climate. The aim of the study was examination, how changes of the West Spitsbergen Current properties and pathways influence the local climate conditions in the Fram Strait region. Results from observations carried in the Nordic Seas by the Institute of Oceanology Polish Academy of Sciences in summers 2000–2007 were compared with time series of air temperature in Spitsbergen and sea ice conditions north of Spitsbergen. We conclude that the heat advected with the West Spitsbergen Current shapes local conditions mostly during the winter. The highest correlations occur between the temperature of Atlantic Water and air temperature as well as the sea ice cover in the following winter. Copyright © 2011 Royal Meteorological Society

KEY WORDS thermohaline circulation; nordic seas; climate change; sea-ice extention

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1. Introduction

The substantial changes in the Arctic climate observed in recent years have generated an urgent need to investigate the Arctic Ocean's heat budget. The transport of warm, saline Atlantic Water (AW) through the Nordic Seas and the Fram Strait is one of the most important components of the global climate system. The conversion of warm surface flow into cold deep currents forces the Thermohaline Circulation (THC) (Hansen *et al.*, 2004). The oceanic heat released during this transformation influences the climate of the Northern Hemisphere. The fresh water storage and ice cover of the Arctic Ocean is also a very important component of the global climate system. For a long time the atmosphere and its warming was seen as the main cause of the shrinking sea ice in the Arctic Ocean. Only recently has the influence of the ocean and its heat transport been recognized as a very important factor affecting changes in sea ice coverage.

The Fram Strait is the only passage between the Atlantic and Arctic Ocean deep enough to permit the throughflow of AW at intermediate levels (Schauer *et al.* 2008). The variability in AW properties and flow structure in the Fram Strait region are therefore very important as regards global and local climatic conditions. Synoptic observations conducted by the Institute of Oceanology, Polish Academy of Sciences (IOPAS) in the West Spitsbergen Current and Fram Strait areas show summer-to-summer changes of AW properties and flow structure. Progressive warming of the West Spitsbergen Current (WSC) has been observed since 2004. During the summers of 2004–2006 the 5 °C isotherm at 100 m depth moved meridionally 4.5° northwards (Walczowski and Piechura, 2007). In summer 2006 the temperature of the AW core reached record high values. In summer 2007 the AW layer temperature decreased – this could be the beginning of a reverse trend in AW temperature.

There are still a lot of questions to be addressed concerning the importance of oceanic heat transport in the global climate in general and the Arctic climate in particular. The atmospheric and oceanic components of poleward heat transport are partitioned: in northern latitudes the largest portion of heat is transported by the atmosphere, but oceanic transport also influences climate significantly, mostly by the Bjerknes compensation mechanism (Swaluw *et al.*, 2007). Not only this partitioning, but also the variability of both components is very important. Large heat transport anomalies could correspond to large climate shifts.

To investigate the role of advective oceanic heat, we analyse the influence of recently observed changes in the WSC's physical properties on local conditions, i.e. in the Fram Strait and Svalbard regions. The first part describes the structure, transformation, and variability of the WSC, and in the second, changes in WSC properties are compared with time series of atmospheric (air temperature) and cryospheric (sea ice cover) properties.

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2. Structure of the West Spitsbergen Current

The West Spitsbergen Current is the northern extension of the global Thermohaline Circulation warm limb. The WSC is supplied by the inflow of AW into the Nordic Seas over the Greenland-Scotland Ridge (Figure 1). Together with the colder and less saline southward outflow, this density- and wind-driven current system is often called the Atlantic Meridional Overturning Circulation (AMOC). The WSC is the prolongation of two main AW streams entering the Nordic Seas: the inflow through the Faroe-Shetland Channel (Shetland branch) and the inflow between Iceland and the Faroes (Faroe branch). Each branch carries 3.8 Sv of AW, and together, the two convey 380 TW of heat (Hansen *et al*., 2008). The continuation of the Shetland branch is the barotropic Norwegian Atlantic Slope Current (NwASC) flowing over the Norwegian slope (Skagseth *et al*., 2004). Having passed northern Norway, the current divides. One part turns east into the Barents Sea, but most of the AW flows along the Barents Sea and Spitsbergen slope as the core of the West Spitsbergen Current. The Norwegian-Atlantic Current (NwAC) is the continuation of the Faroe inflow (Orvik and Niiler, 2002). This mostly baroclinic current is also bottom-topography-guided and flows over the submarine ridges system. In the northern part, the current flows as the western branch of the West Spitsbergen Current (Walczowski and Piechura, 2006). At 79°N the two branches converge (Walczowski and Piechura, 2006), but then divide again into two or even three branches. The easternmost branch (Svalbard Branch, SB) continues over the Svalbard slope into the Arctic Ocean and circulates cyclonically (Rudels *et al*., 1999), becoming covered by fresher and colder waters. The central flow (Yermack Branch, YB) continues northwards over the shallow Yermack Plateau. The western branch of AW recirculates mostly west- and southwestwards as the Return Atlantic Current (RAC).

The velocities of AW advection in the various branches are different. The warm anomalies observed in the WSC core move with a mean speed of 3.6 cm/s (Polyakov *et al*. 2005); the mean signal propagation velocity in the western branch is lower, approximately 1.9 cm/s (Walczowski and Piechura, 2007).

During its northward flow, AW undergoes intense transformation (Figure 2): it cools as a result of large heat fluxes to the atmosphere, and freshens and cools as it mixes with ambient, less saline and colder waters. In the Nordic Seas, heat fluxes to the atmosphere and ice melting by AW are one of the most important climatological factors. It maintains the region free of ice, allowing intense ocean–atmosphere heat exchange during winter. At this season, convective mixing in the temperature-stratified water column reaches deep below the seasonal thermocline. This suggests that advective oceanic heat transport plays a very important role in the total heat balance of this region.

3. Data and methods

This paper is based on CTD (Conductivity, Temperature, Depth) data gathered from 2000 to 2007 by the Institute of Oceanology, Polish Academy of Sciences, from on board the R/V *Oceania*. The stations covered the Atlantic Domain of the Greenland Sea (Figure 3) and were occupied each summer, at the same time between 20 June and 20 July. CTD data for the southernmost section for summers 2004–2007 were provided by the

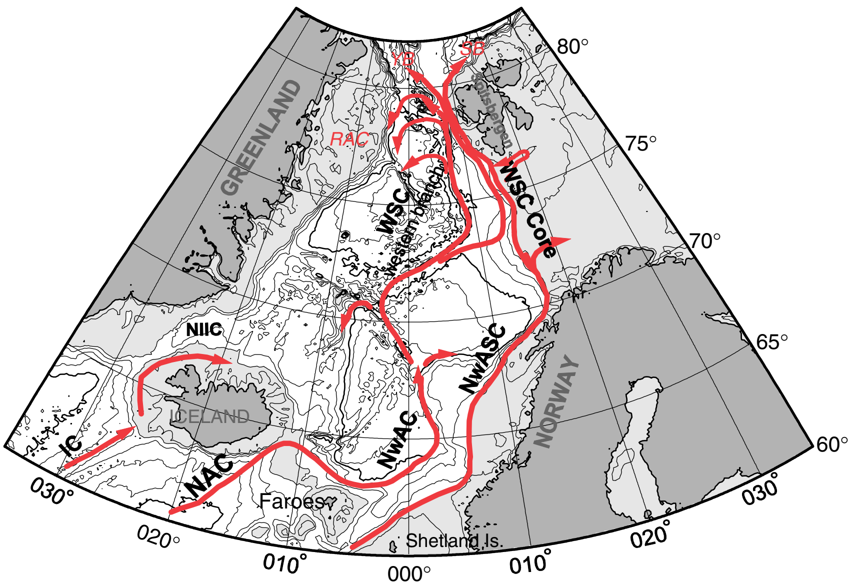

Figure 1. Main pathways of Atlantic Water in the Nordic Seas (Walczowski and Piechura, 2006). (IC: Irminger Current; NIIC: North Icelandic Irminger Current; NAC: North Atlantic Current; NwAC: Norwegian-Atlantic Current; NwASC: Norwegian Atlantic Slope Current; WSC: West Spitsbergen Current; SB: Svalbard Branch; YB: Yermack Branch; RAC: Return Atlantic Current). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

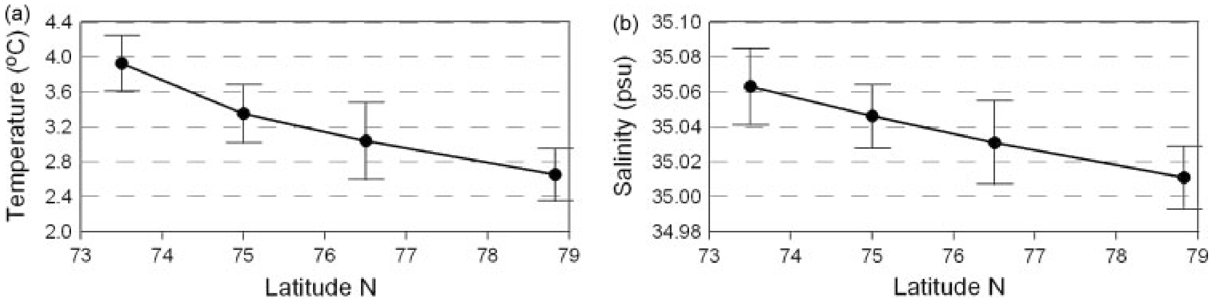

Figure 2. Summers 2000–2007: mean summer temperature (a) and salinity (b) of Atlantic Water as a function of northerly latitude.

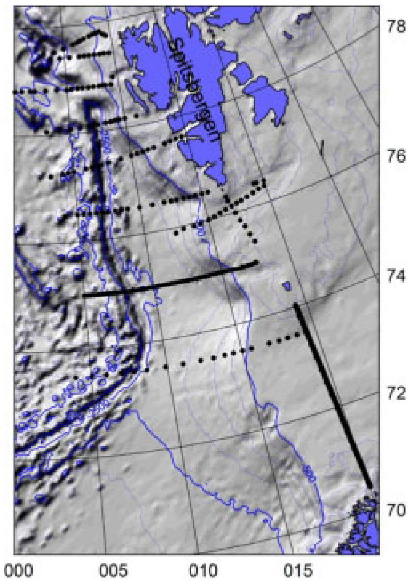

Figure 3. Station grid usually occupied by R/V *Oceania* during 'AREX' cruises. Transects 'V 1' and 'K' are marked in bold. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Institute of Marine Research, Bergen. Data were collected within the framework of the UE projects ASOF-N and DAMOCLES.

The mean properties of AW were calculated from the same area of 313 000 km^2 covered every year. The means were weighted by the AW layer thickness. AW was parameterized by 34.92 salinity and 0 °C temperature. Heat content and transport were calculated with reference to temperature −0.1 °C. At horizontal distributions, geostrophic baroclinic currents were computed from the hydrography with reference to the 1000 dbar no-motion layer. Geostrophic transport in vertical sections was calculated from the bottom to the surface.

Data were collected only once a year, but always during the same period: this minimizes the influence of the seasonal cycle of water properties on the results. Also, averaging data over large areas and a thick water layer gives more reliable results. Nevertheless, when interpreting data we can only talk about summer-to-summer variability.

For comparison, meteorological data from the Polish Polar Station in Hornsund, southwestern Svalbard, were used. Belonging to the Institute of Geophysics, Polish Academy of Sciences, this station is part of the Norwegian stations network and is registered at the WMO by number 01003. The Hornsund temperature variability correlates well with the Longyearbyen air temperature, and in the present work this time series is treated as an indicator of processes at a bigger (western Svalbard) scale. The monthly mean data were provided by the Institute of Geophysics, Polish Academy of Sciences.

4. Temporal variability in WSC properties

In recent years the properties, volume and heat transport of AW has been highly variable. The mean AW layer temperature reached its minimum in summer 2003, increased by more than 0.4 °C in 2004 and by more than 0.3 °C in 2005–2006 (Figure 4). The decrease in 2007 was of the same order as the increase in 2004. The salinity of the AW layer also changed, with a maximum in 2005 and also started to decrease one year earlier before the temperature (Figure 4).

Total baroclinic velocities (Figure 5), volume and heat transport changed simultaneously with the AW temperature changes.

There were two distinct regimes of the baroclinic current pattern: cold (Figure 6a) with intensification of eastward flows, and warm (Figure 6b) with strong flows towards the Fram Strait. During the warm period the mean northerly component of the baroclinic currents increased to 2.5 cm/s, and the northward range of the 5 °C isotherm was much greater than during the cold one.

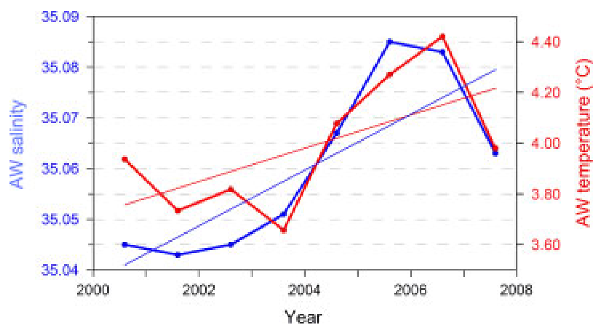

Figure 4. Mean AW layer temperature (red line) and salinity in summers 2000–2007. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

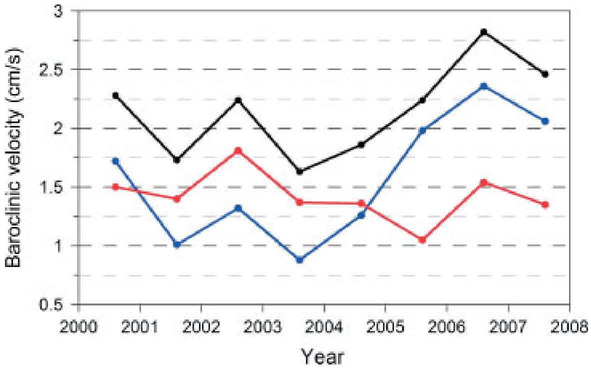

Figure 5. Mean baroclinic velocities at 100 dbar: total (black line), northward V component (blue line) and eastward U component (red line).

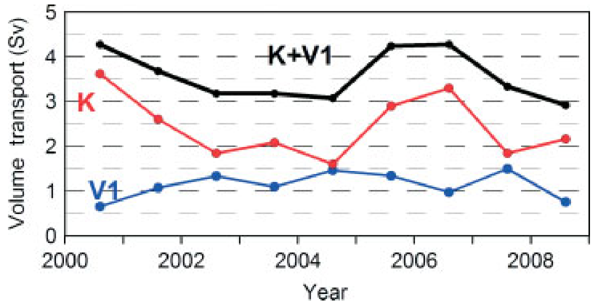

Figure 7. Baroclinic AW volume transport into the Barents Sea (blue line) and towards the Fram Strait (red line), and the sum of both transports (black line).

The important question is whether these flow changes compensate one another. Baroclinic calculations for transect V1, crossing the Barents Sea Opening – the area between northern Norway and Bear Island – and transect 'K' along latitude 75°N (Figure 3) were compared. Indeed, the results show that during the intensive northward transport, the volume transport into the Barents Sea was lower (Figure 7). However, the sum of both transports also changed over time. The variability in the northward flow across the 75°N parallel is much greater than the variability of inflow into the Barents Sea. In summers 2005–2006 the intensification of northward transport was greater than the decrease in eastward transport. This means that the change in AW transport is not the only consequence of the partition of AW between the Barents Sea and the Fram Strait.

Skagseth *et al.* (2008) show that inflow into the Barents Sea is enhanced by specific atmospheric conditions – a low-pressure system extending southwest of Iceland into the Barents Sea. A depression north of Bear Island may cause the northward AW flow to intensify.

The IOPAS investigation shows that the intense activity of the western WSC branch, especially the great anticyclonic eddies carrying large heat anomalies, was very important as regards the increase in northward transport and raising the AW temperature in 2005–2006 (Walczowski and Piechura, 2007). The eddies were much larger than the frontal mesoscale features usually observed (Piechura and Walczowski, 1995). The origin of the eddies is not well known: they probably came into being in the Lofoten Basin and advected slowly northwards along the line of submarine ridges.

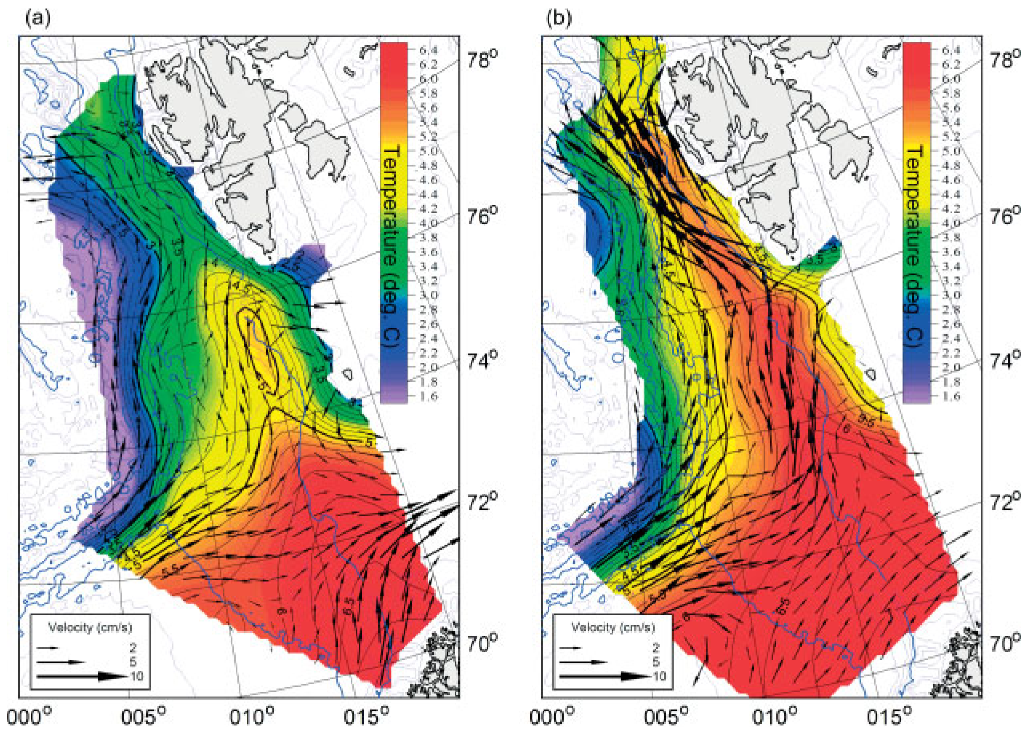

Figure 6. Temperature (color scale) and baroclinic currents at 100 dbar in (a) summer 2003 and (b) summer 2006.

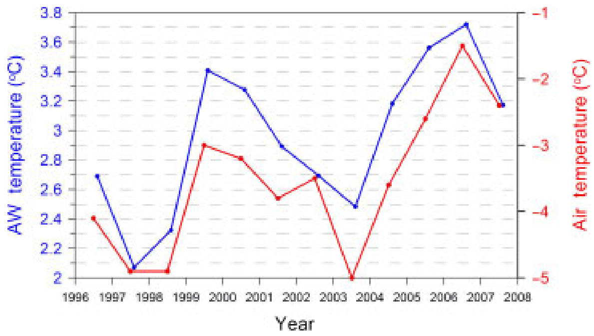

Figure 8. Mean AW layer temperature along transect 'N' in summers 2000–2007 (blue line) and annual mean air temperature at Hornsund (red line). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

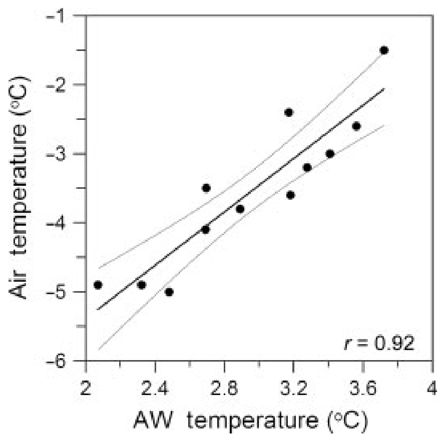

Figure 9. Correlation between the AW mean temperature along transect 'N' in summers 2000–2007 and the annual mean air temperature at Hornsund in 2000–2007. The 95% confidence limit is marked.

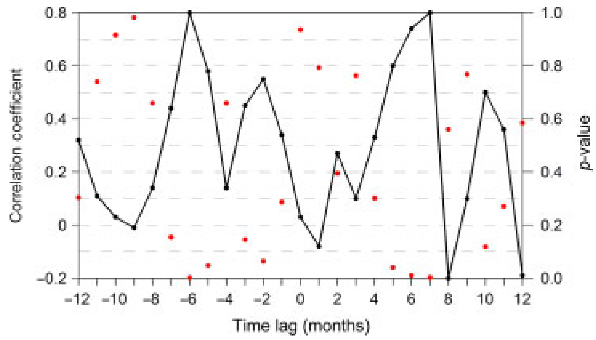

Figure 10. Lagged correlation between the AW mean temperature along transect 'N' in summers 2000–2007 and the mean monthly air temperature at Hornsund in 2000–2007 (solid line) and p-test values (red dots). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

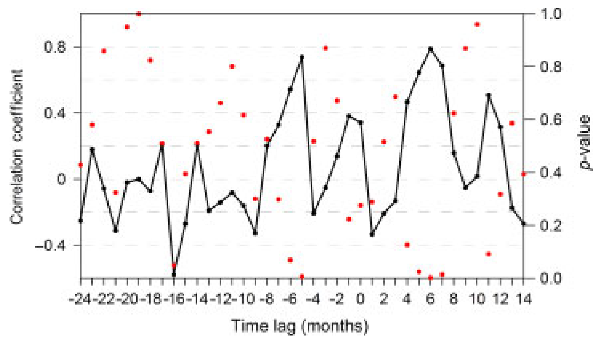

Figure 11. Correlation coefficient between AW temperature along transect 'N' and lagged ice-free surface around Svalbard (solid line) and p-test values (dots) (Piechura and Walczowski, 2009). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

5. Atlantic water variability and the local climate

To find out how these significant changes in AW temperature and heat transport influence the local climatic conditions, meteorological data from southwestern Svalbard were analysed. The results show that both the variation in the mean AW temperature over the entire investigated region and at several sections are well correlated with the changes in the mean air temperature at Hornsund. In this paper, we compare the yearly mean temperatures from the Hornsund meteorological station with the IOPAS time series of data from transect 'N' along the 76°30′N parallel. The mean AW summer temperature changes from 2.1 °C to 3.7 °C, and the amplitude of the annual mean air temperature is higher, from −5 °C to −1.5 °C. Nevertheless, the shapes of both curves are very similar (Figure 8), which results in a high positive correlation (correlation coefficient $r = 0.92$) (Figure 9).

To investigate the cause of such a high correlation, time-lagged correlation coefficients between the summer oceanographic measurements and the monthly mean meteorological data were calculated; the results (Figure 10) do not provide convincing evidence. The high correlation and low p-test values for the 5–7-month time lag suggest that the high AW temperature during summer influences the air temperature at Hornsund the following winter. But there are also high correlations for the previous winter's air temperature (a – 6-month time lag). These results show that advection of AW is very slow and that the changes in AW properties are continuous: the changes in water properties observed during the summer could have begun during the previous winter. On the other hand, winter air temperature and air-sea exchange conditions also influence the properties of AW.

6. The effect of Atlantic Water changes on sea ice

A similar correlation structure could be obtained by comparing the sea ice cover around northern Svalbard and the AW temperature along transect 'N' (Figure 11). The best correlation between the summer AW temperature and the ice-free area was found for the next winter, but the correlation for the previous winter was also high. The correlation was lowest for short time lags (Piechura and Walczowski, 2009).

7. Discussion and conclusions

The results show that AW influences the climate and ice conditions of Svalbard. By releasing large heat fluxes into the atmosphere, especially during winter (up to 300 W/m^2), AW significantly influences the winter air temperature. During the summer this influence is not so great – ocean–atmosphere heat fluxes are less intense because the air temperature is higher than during the winter. These results confirm that oceanic heat advection is very important for the heat budget of the Fram Strait region during the winter. At these latitudes the oceanic heat stored in the mixed layer during the summer is exhausted by November-December (Rhines *et al.*, 2008), and winter ocean–atmosphere fluxes are maintained by advected heat. That is why the winter air temperature is so strongly correlated with changes in water properties. Lead/lag correlations do not give a definitive answer to the cause/effect question; AW temperatures measured during the summer are well correlated with the air temperatures in both the previous and the next winter. However, at a longer time scale, north of latitude 70°N, the ocean usually leads the atmosphere (Swaluw *et al.*, 2007).

The situation is very similar as regards the ice cover. During winter, warm AW is the only factor that can melt ice, whereas during the summer the extent of ice cover is governed by solar radiation, winds stress, drift, and oceanic heat fluxes.

Temporal changes in AW properties in the Fram Strait region depend on the upstream AW properties, branching and the northward advection velocity. Calculated baroclinic transports to the Barents Sea are of the same order as those measured by a Norwegian current meter array: an annual mean of 1.8 Sv (Skagseth *et al.*, 2008). This transport changes over time, but variations do not compensate for the increasing northward volume transport during the warm periods. IOPAS investigations show that the main cause of the increase in northward volume and heat transport was the intensification of the northward currents. The results from the mooring array in Fram Strait confirm that such intensification took place in 2005 and 2006 (Schauer *et al.*, 2008).

Another interesting problem is feedback. The effect of amplification – the increase in signal strength during the northward advection of temperature anomalies – is well known. Similar effects were observed during the 2005–2006 northward propagation of the warm AW tongue. The increase in northward velocities caused the AW temperature to rise (shorter exposure time), and the higher AW temperature generated a faster flow (stronger baroclinic forcing), thus closing the feedback loop.

There is also the important question of how local conditions influence AW properties. Correlations with a negative time lag may suggest that the atmosphere exerts a strong influence on AW variability. The intensive transformation of AW en route through the Nordic Seas may support this hypothesis. The conditions of ocean–atmosphere heat exchange depend on water–air temperature differences, wind intensity and direction, ice cover, air humidity, etc. All these factors change over time. The rate of transmitted heat also depends strongly on advection velocity: this means that the temperature changes recorded in the Fram Strait are the effect of not only upstream AW variability, but are also generated at a local scale, in the Nordic Seas.

To acquire a better understanding of all these processes and feedbacks, longer time series and more comprehensive investigations are necessary.

References

Hansen B, Østerhus S, Quadfasel D, Turrell W. 2004. Already the Day After Tomorrow? *Science* **305**: 953–954.

Hansen BS, Østerhus W, Turrel S, Jonsson H, Valdimersson H, Hatún S, Olsen . 2008. The Inflow of Atlantic Water, Heat and Salt to the Nordic Seas Across the Greenland-Scotland Ridge, In: *Arctic-Subarctic Ocean Fluxes*, Springer: Dordrecht; pp. 15–43.

Orvik KA, Niiler P, 2002. Major pathways of Atlantic water in the northern North Atlantic and the Nordic Seas toward the Arctic. *Geophysical Research Letters* **2919**: 1896, L015002, DOI:10.1029/2002GL015002.

Piechura J, Walczowski W. 1995. The Arctic Front: structure and dynamics. *Oceanologia* **371**: 47–73.

Piechura J, Walczowski W. 2009. Warming of the West Spitsbergen Current and sea ice north of Svalbard. *Oceanologia* **51**(2): 147–164.

Polyakov IV, Beszczynska A, Carmack EC, Dmitrenko IA, Fahrbach E, Frolov IE, Gerdes R, Hansen E, Holfort J, Ivanov VV, Johnson MA, Karcher M, Kauker F, Morison J, Orvik KA, Schauer U, Simmons HL, Skagseth Ø, Sokolov VT, Steele M, Timokhov LA, Walsh D, Walsh JE. 2005. One more step toward a warmer Arctic. *Geophysical Research Letters* **32**: L17605, DOI:10.1029/2005GL023740.

Rhines P, Häkkinen S, Josey SA. 2008. Is Oceanic Heat Transport Significant in the Climate System? In: *Arctic-Subarctic Ocean Fluxes*, Springer: Dordrecht; pp. 87–110.

Rudels B, Fredrich HJ, Quadfasel D. 1999. The Arctic circumpolar boundary current. *Deep-Sea Research Pt. II* **46**: 1023–1062.

Schauer U, Beszczynska-Moeller A, Walczowski W, Fahrbach E, Piechura J, Hansen E. 2008. Variation of measured heat flow through the Fram Strait between 1997 and 2006, In: *Arctic-Subarctic Ocean Fluxes*, Springer: Dordrecht; pp. 65–85.

Skagseth Ø, Furevik T, Ingvalsen R, Loeng H, Mork KA, Orvik KA, Ozhigin V. 2008. Volume and Heat Transport to the Arctic Ocean Via the Norwegian and Barents Seas, In: *Arctic-Subarctic Ocean Fluxes*, Springer: Dordrecht; pp. 45–64.

Skagseth Ø, Orvik KA, Furevik T. 2004. Coherent variability of the Norwegian Atlantic Slope Current derived from TOPEX/ERS altimeter data. *Geophysical Research Letters* **31**: L14304, DOI:10.1029/2004GL020057.

Van Der Swaluw E, Drijfhout SS, Hazeleger W. 2007. Bjerknes Compensation at High Northern Latitudes: The Ocean Forcing the Atmosphere. *Journal of Climate* **20**: DOI:10.1175/2007JCLI1562.1.

Walczowski W, Piechura J. 2006. New evidence of warming propagating toward the Arctic Ocean. *Geophysical Research Letters* **33**: L12601, DOI:10.1029/2006GL025872.

Walczowski W, Piechura J. 2007. Pathways of the Greenland Sea warming. *Geophysical Research Letters.* **34**: L10608, DOI:10.1029/2007GL029974.

