Papers

Warming of the West Spitsbergen Current and sea ice north of Svalbard*

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Abstract

According to the results of recent research, besides the atmospheric circulation, it is heat transport to the Arctic Ocean (AO) by ocean currents, the West Spitsbergen Current (WSC) in particular, that is playing a significant role in the process of Arctic warming. Data collected by the Institute of Oceanology, Polish Academy of Sciences (IO PAS), in the Norwegian and Greenland Seas, and Fram Strait during the last 20 years reveal considerable changes in the amount of heat transported by the WSC into the Arctic Ocean. An increase in Atlantic Water (AW) temperature and the intensification of heat transport were observed in

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2004–06; after this period, both parameters decreased. The aim of this study was to find out whether the fluctuations in heat input by the WSC have influenced the sea-ice distribution around Svalbard. In fact they do, but oceanic heat transport should nonetheless be regarded as just one of many processes influencing sea-ice behaviour.

1. Introduction

1.1. Sea ice retreat in the Arctic Ocean

The extent and thickness of Arctic Ocean ice has been decreasing for many years. In the summer of 2007, there was an unpredicted, dramatic reduction to 4.28 million km^2, which is 1.29 million km^2 less than the previous minimum in September 2005. Some numerical models even predict an ice-free Arctic Ocean by 2013 (Whelan et al. 2007; W. Maslowski – Naval Postgraduate School, personal communication, December 2007). This could introduce a new factor into the processes and consequences of global climate change.

Why this happened and why this event could not be predicted has become an extremely urgent question. This problem was the main subject of discussion at the Arctic Observation Integration Workshops held in Palisades (NY) in March 2008 (see Workshop reports www.arcus.org). It concluded that in 2007, in the wake of long-term preconditions – atmospheric warming, reduced winter cooling, a longer melting period, a sea-ice thickness reduced by about 1 m during the last 20 years, and an increase in long-wave radiation – came the short-term trigger, specific to 2007: atmospheric forcing, the type of weather and increased solar radiation. One more reason was mentioned there as well: warm water of Atlantic origin moving up from depths of 300–400 m close to the surface (R. Woodgate's presentation at the workshop, www.arcus.org); this was substantiated by the observation of ice melting from its bottom (D. Perovich's presentation, www.arcus.org). The rapid increase in Atlantic Water layer temperature in the Laptev Sea, recently recorded with an MMP mooring (Polyakov et al. 2005), also supports this idea, as does the data obtained by IO PAS from mooring M5 located over the slope of Severnaya Zemlya (3.19°C at 100 m depth in January 2007).

It seemed reasonable to examine whether and how the changes, recorded by IO PAS (Walczowski & Piechura 2006, 2007), in the temperature and heat content of Atlantic Water carried by the West Spitsbergen Current could influence the ice conditions in the nearest sea area, just to the north of Svalbard.

1.2. Atlantic Water in the Nordic Seas

The northward flow of Atlantic Water is very important for the local and global climate. Together with the colder and less saline southward outflow, it maintains the Thermohaline Circulation in the Nordic Seas. The total volume transport of AW into the Nordic Seas has recently been estimated at between 7.7 Sv (10^6 m^3 s^{-1}) and 9 Sv (Hansen et al. 2008), and the heat transport from 276 TW (10^{12} W) to 310 TW. AW inflow into the Nordic Seas is maintained by three main streams (Hansen & Østerhus 2000) (Figure 1).

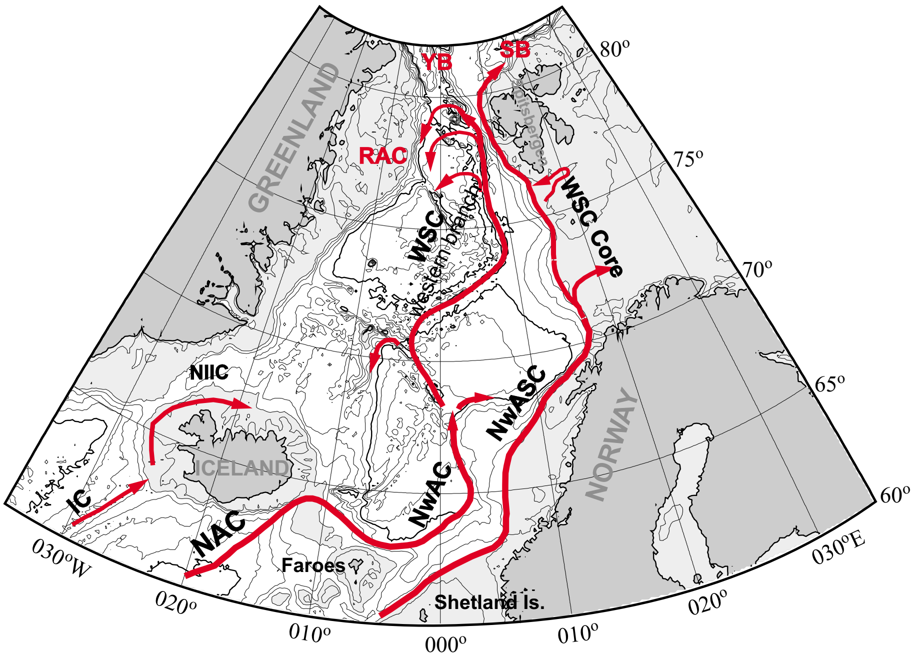

Figure 1. Main pathways of Atlantic Water in the Nordic Seas:

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
RAC	– Return Atlantic Current
YB	– Yermack Branch
SB	– Svalbard Branch

That between Iceland and Greenland is the weakest, transporting about 1 Sv of the total AW volume (Jónsson & Briem 2003) and 25 TW of the heat. The most intensive is the central, Faroe branch, which carries 3.5 Sv of the AW volume and 127 TW of the heat. The inflow between the Faroes and the Shetlands through the Faroe-Shetland Channel (Shetland branch) carries 3.2 Sv of AW and 127 TW of heat. The continuation of the Shetland branch is the barotropic Norwegian Atlantic Slope Current (NwASC) flowing over the Norwegian slope (Skagseth et al. 2004). After passing northern Norway, the current divides: one part turns east into the Barents Sea, most of the AW flowing along the Barents Sea and Spitsbergen slope as the core (eastern branch) of the West Spitsbergen Current. The mostly baroclinic Norwegian-Atlantic Current (NwAC) is a continuation of the Faroe inflow (Orvik & Niiler 2002). This current is also guided by bottom topography. In the Greenland Sea the flow continues over the submarine ridges as the western branch of the West Spitsbergen Current (Walczowski & Piechura 2006).

During its northward flow Atlantic Water undergoes a dramatic transformation: it cools as a result of large heat fluxes to the atmosphere, and freshens and cools further as a consequence of being mixed with less saline and colder adjacent waters. Finally, AW reaching Fram Strait is 6°C colder, carrying six times less heat than was transported over the Greenland-Scotland Ridge (Schauer et al. 2008). But even this heat is not all transported into the Arctic Ocean. After the two WSC branches converge at latitude 78°N (Walczowski et al. 2005, Walczowski & Piechura 2006), the AW inflow divides again into two or even three branches. The easternmost branch (Svalbard Branch, SB) continues over the Svalbard slope, flows into the Arctic Ocean, where it circulates cyclonically (Rudels et al. 1999) and is 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 west and south-westwards as the Return Atlantic Current (RAC).

In recent years, properties, volume and heat transport of AW have been observed to be highly variable; these variations have influenced ice conditions in Fram Strait region.

2. Data and methods

This work is based on CTD, Vessel Mounted Acoustic Doppler Current Profiler (VmADCP) and Lowered Acoustic Doppler Current Profiler (LADCP) data collected between 2000 and 2008 by the Institute of Oceanology (Polish Academy of Sciences) from on board the r/v 'Oceania'. A dense grid of stations (Figure 2) was operated between 20 June and 20 July each summer. The stations and transects cover the whole area of the

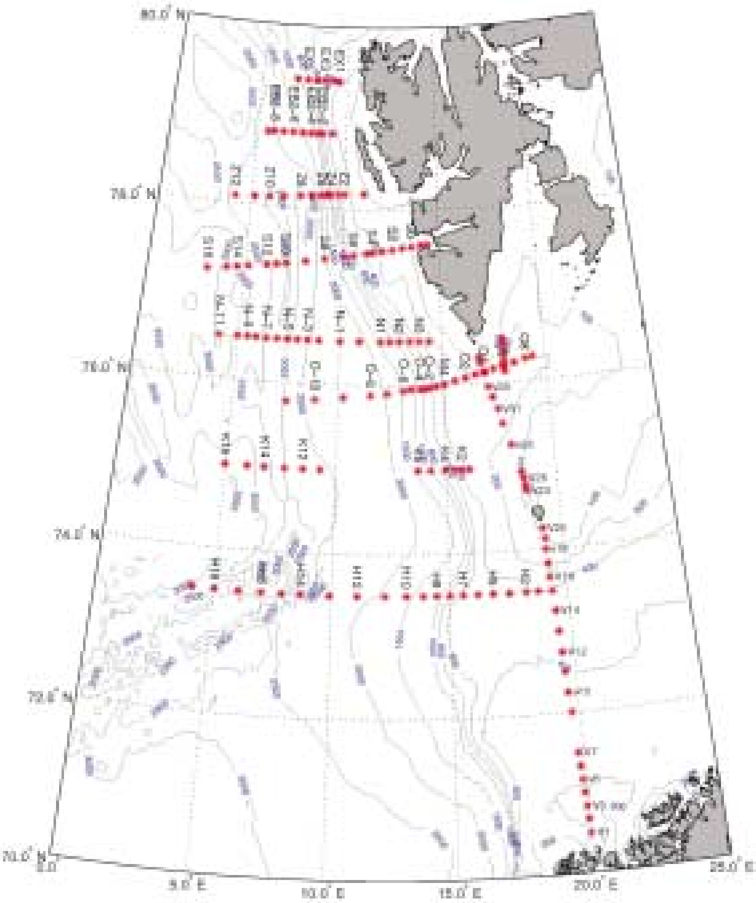

Figure 2. The CTD and LADCP station grid usually occupied during the AREX cruises

WSC. For the last four cruises, the CTD data for the southernmost section were obtained by the Institute of Marine Research in Bergen, which kindly supplied them to us.

The mean properties of AW were calculated from the same area of 313 000 km^2 covered every year. Means were weighted by the AW layer thickness. Atlantic Water was parameterised at temperature $> 0°C$ and salinity > 34.92 PSU (Walczowski & Piechura 2006). Heat content and transports were calculated with reference to $-0.1°C$ and all anomalies with reference to the summer means (2000–08).

Baroclinic transports across the transects were calculated from the surface to the bottom.

3. Results

3.1. Changes in AW properties

Significant changes were observed in both the mean AW layer properties (Table 1) and the properties on particular transects or levels.

Table 1. Mean properties of the AW layer in the investigated area in summers 2000–08

Properties	2000	2001	2002	2003	2004	2005	2006	2007	2008
salinity [PSU]	35.045	35.043	35.045	35.051	35.067	35.085	35.083	35.063	35.051
temperature [°C]	3.937	3.734	3.818	3.657	4.078	4.271	4.421	3.980	3.593
layer thickness [m]	466.5	470.2	480.7	501.9	498.9	482.8	475.3	476.5	492.0
AW volume [10^3 km^3]	146.31	147.48	150.77	157.43	156.50	151.45	149.07	149.45	154.31
heat content [10^{21} J]	2.355	2.231	2.285	2.294	2.559	2.607	2.631	2.373	2.216

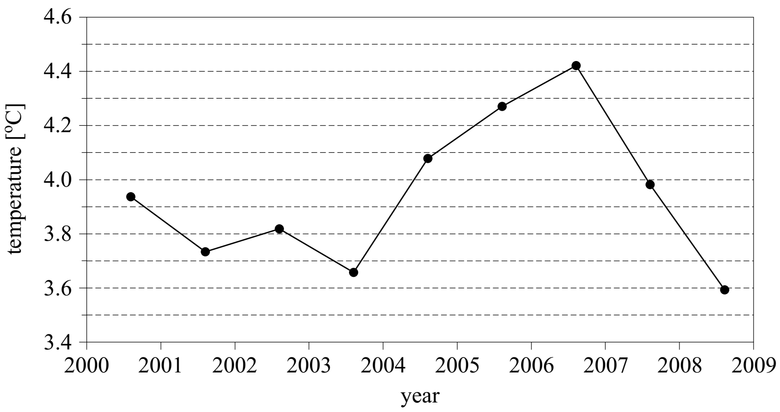

Figure 3. Mean Atlantic Water layer temperature, summers 2000–08

During the study period the Atlantic Water temperature fluctuated significantly. The mean temperature of the AW layer changed little during summers 2000–03, but rose rapidly, by nearly 0.8°C, in the next 3 years. Thereafter (2007–08) it decreased by > 0.4°C each year (Figure 3).

A very spectacular development took place in the northward shift of warm water in 2004–06: for example, at 100 dbar the 5°C isotherm moved by nearly 5° of latitude, from 74°30′N in 2004 to 76°30′N in 2005 and to its northernmost extent at latitude 79°N in 2006 (Figure 4). In summers 2007 and 2008 the 5°C isotherm moved back southwards, to the same locations as in 2005 and 2004 respectively. The position of the 5°C isotherm is treated here as an indicator of AW warming.

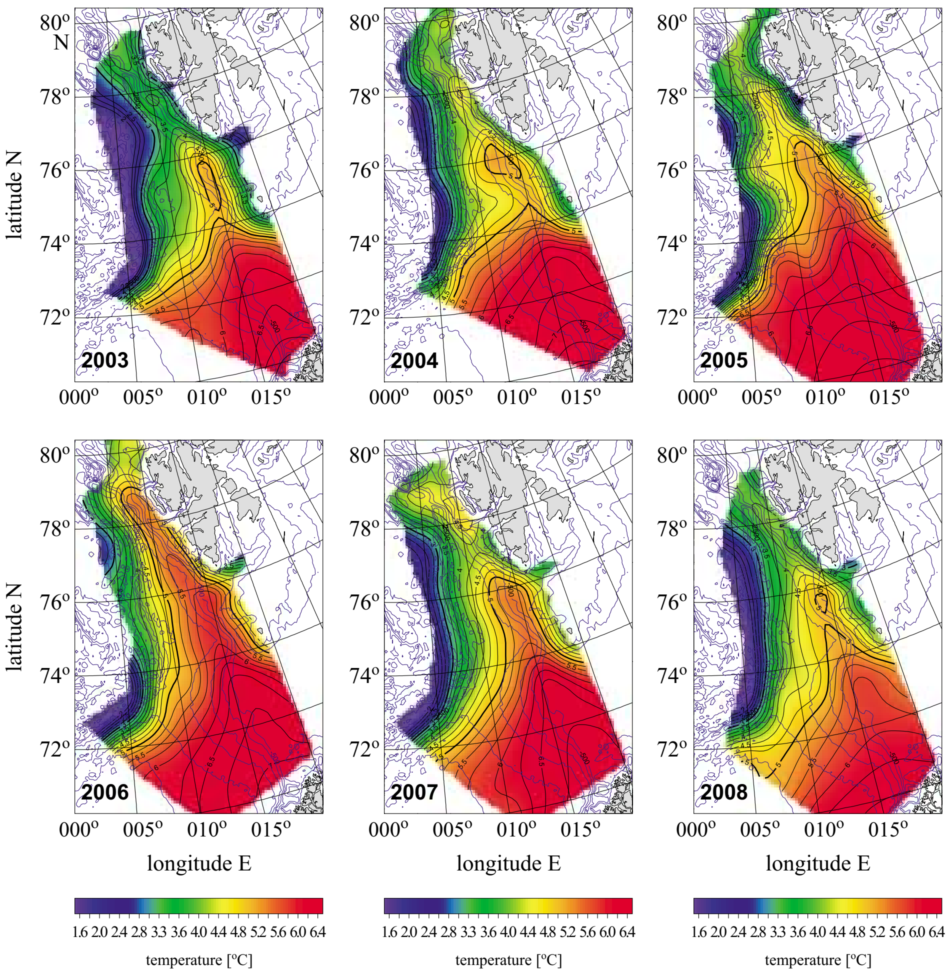

Figure 4. Temperature at 100 dbar, summers 2003–08. The 3°C and 5°C isotherms are thickened

From one summer to the next the mean thickness of the AW layer in the study area varied between 467 m and 502 m: from the smallest thickness in

2000 it increased to the greatest in 2003, after which it decreased until 2006; in 2008 the layer again thickened (Table 1). The horizontal distribution of this parameter exhibits (Figure 5) much greater differences. In the summers of 2002, 2003 and 2004, the thick AW layer (> 600 m) was spread over a larger area, i.e. its volume was greater, whereas in 2000, 2001, 2006 and 2007 the exact reverse was the case. The distributions of AW layer thickness show a very interesting feature, namely, circular areas where AW reaches much greater depths than usual. What is even more intriguing is that these areas were found almost every summer at the same locations – to the south-west of the tip of southern Svalbard (Soerkapp) and in the Fram Strait.

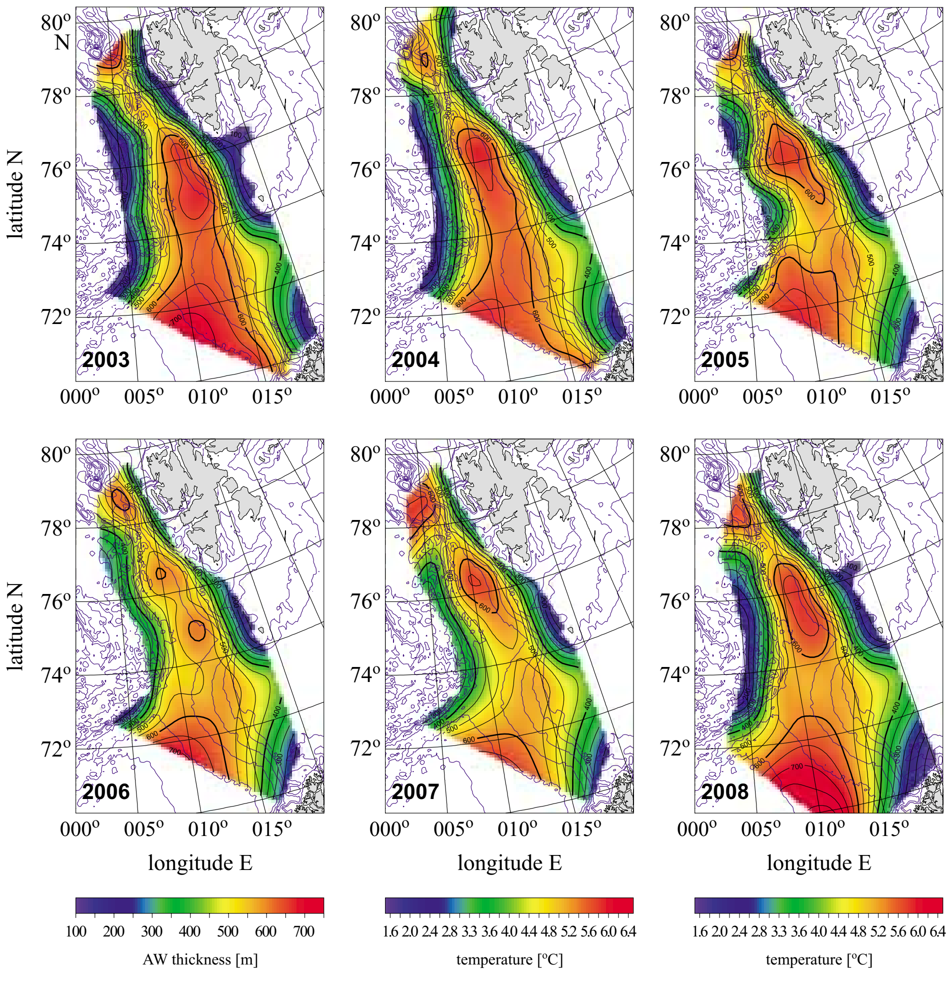

Figure 5. AW layer thickness, summers 2003–08. The 400 and 600 m isolines are thickened

Such phenomena are usually associated with anticyclonic eddies. Eddy activity seems to be worthy of closer investigation, especially from the point of view of heat transport to the Arctic Ocean.

The variability in heat content depended on both the volume of Atlantic Water and its temperature changes. Low in summer 2001, the heat content grew slowly until 2003 and then increased rapidly by $> 2.5 \times 10^{20}$J in 2004 (Figure 6, Table 1). In the summers of 2005 and 2006, there was little increase in heat content due to the lower AW volume, in spite of the above-mentioned large temperature rise. The following summer there was a big drop in the heat content, nearly equivalent to the 2004 increase, which was caused mainly by the fall in AW temperature.

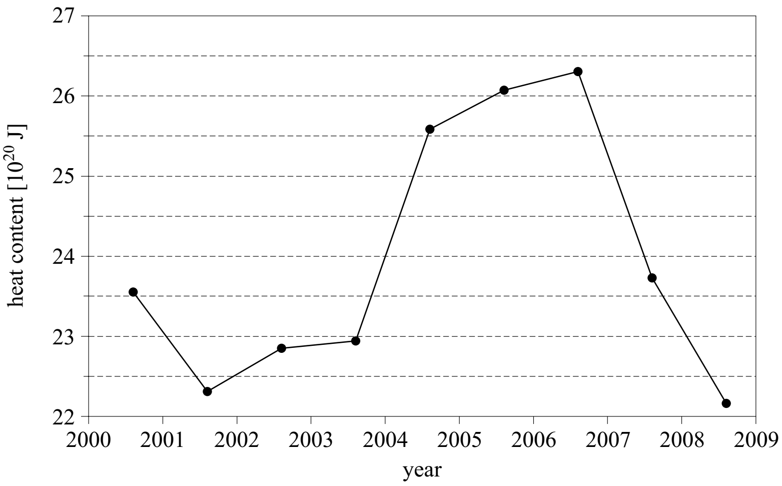

Figure 6. Heat stored in the AW layer [10^{20} J], summers 2000–08

The increasing heat content and activity of the particular branches is well documented by the Hovmoeller plot for the transect along latitude 76°30′N, between 04°E and 15°E in summers 1996–2007 (Figure 7).

The volume and heat transport across the transect along lat. 76°30′N was estimated from a calculation of baroclinic currents (Figure 8). This shows quite a large increase in both parameters in 2003–06. The baroclinic heat transport follows the volume transport; changes in AW temperature are less important for heat transport than changes in the current intensity.

Additional information on the changes in heat content and transport is given by the heat content anomaly (Figure 9). In summers 2000–03 negative anomalies prevailed, whereas in 2004–06 the anomalies were very strongly positive. The anomalies also show how heat is transported northwards: the horizontal distributions make it clear that mesoscale structure,

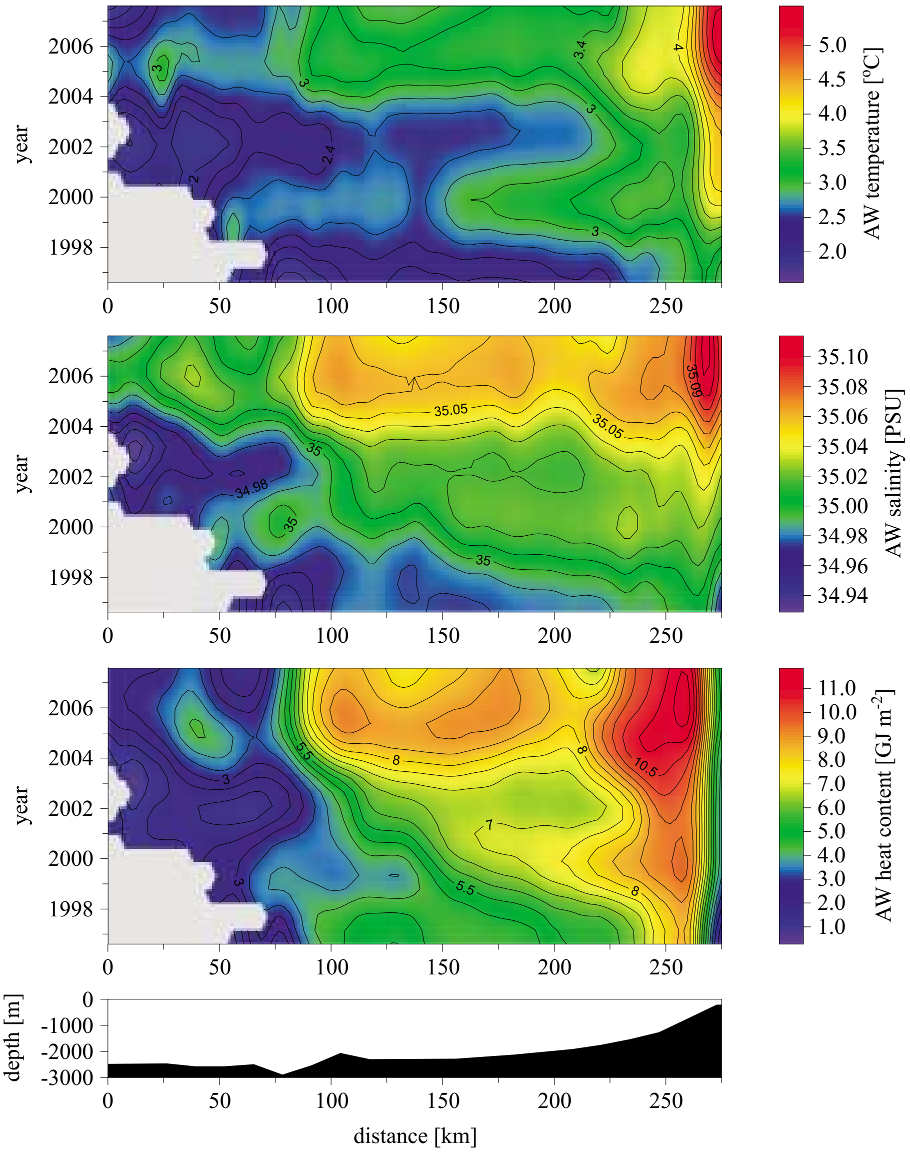

Figure 7. Hovmoeller plot of mean temperature [°C], salinity [PSU] and heat content [GJ m^{-2}] in transect 'N' along latitude 76°30′N, between 04°E and 15°E, summers 1996–2007

and anticyclonic eddies in particular, play a significant role in this process. Usually, these structures are very stable for a long time. For example, the very large eddy observed in summer 2005 in the western branch of the WSC at latitude 73°N was over 170 km in diameter and reached a depth of over 900 m (Walczowski 2009). It carried c. 2.3×10^{19} J of surplus heat. Moving

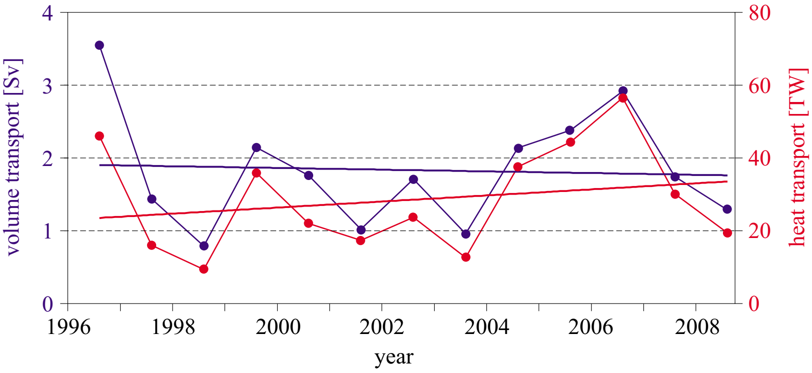

Figure 8. Baroclinic volume [Sv] and heat transport [TW] across transect 'N' in summers 1996–2008

northwards with a mean signal propagation speed of 19 cm s^{-1} (Walczowski & Piechura 2007), the eddy was able to reach Fram Strait by the following summer. It was still carrying a heat surplus (2.5–5 $\times$ 10^{19} J, depending on the area considered), enough to melt 90 000–180 000 km^2 of 1 m thick ice if released.

3.2. Ice cover north of Svalbard

The question is whether and to what extent such large portions of additional heat can influence ice conditions in the Arctic Ocean, especially in the vicinity of Fram Strait. To determine whether the properties of AW affect the ice cover in the Svalbard Region, Special Sensor Microwave Imager (SSM/I) daily data were used (Spreen et al. 2008). The ratio of the ocean area free of ice to the total area of ocean around Svalbard (Figure 10) was calculated. An ice concentration $> 90\%$ was treated as constant ice cover.

The daily values and calculated monthly means reveal a weak positive trend in the ice-free area during recent years (Figure 11). The time series of monthly means were compared with results from the longest IO PAS time series of AW temperature from transect 'N' along latitude 76°30′N (Figure 12). Temperature seems to be a better characteristic than heat transport, because it is stable for a longer time; lagged correlations between AW temperature and ice cover were therefore calculated. Because AW temperature and advection were recorded only once a year, negative time lags (ice conditions in the winter ahead compared with AW temperature the following summer) were also considered.

There is no correlation between AW temperature and ice cover during the same summer (Figure 13). A higher correlation exists for AW temperature and ice coverage during the winter before the AW

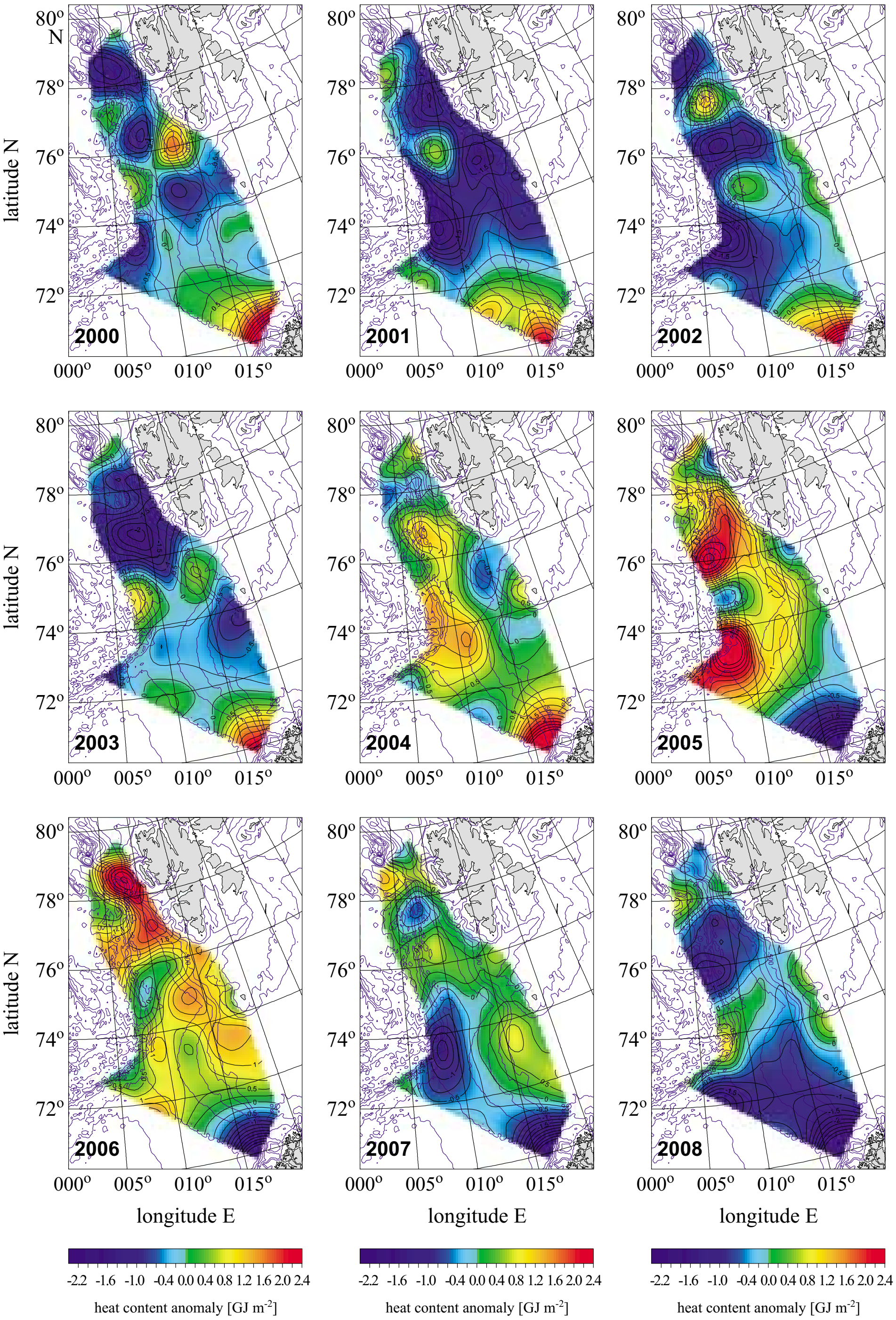

Figure 9. Heat content anomaly [GJ m^{-2}] stored in the Atlantic Water layer, summers 2000–08

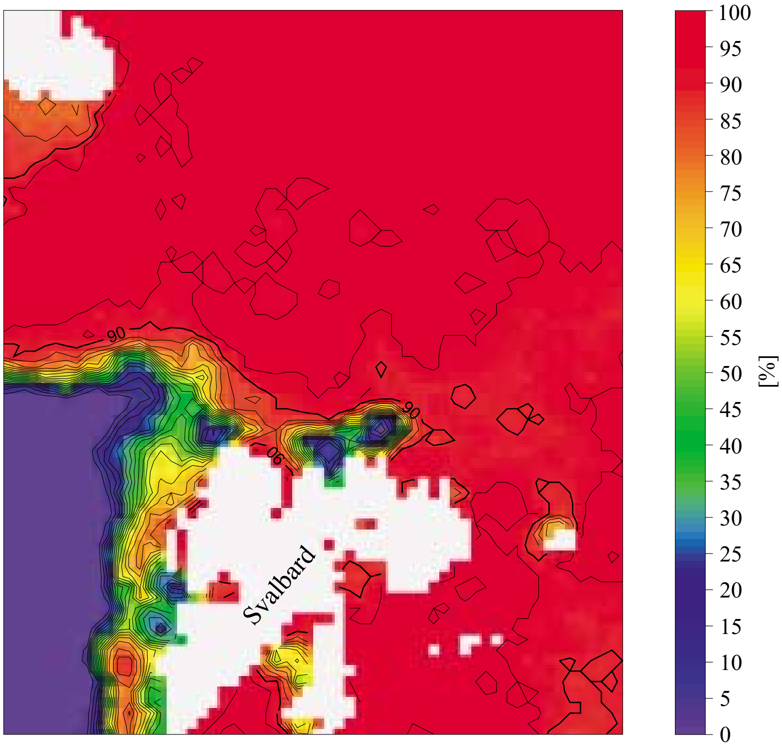

Figure 10. Ice concentration (percent) in the Fram Strait area, 30 January 2004

Table 2. Correlation coefficients and p-tests for AW temperature for the whole transect 'N', its western and eastern ends, and the sea-ice area around Svalbard in winter (December–January–February) before and after AW measurements. Raw data

	Ice-free area, the winter before	p-test	Ice-free area, the winter after	p-test
TAW	0.64	0.0240	0.85	0.0005
TAW_east	0.69	0.0121	0.69	0.0124
TAW_west	0.58	0.0470	0.88	0.0002

measurements, the highest correlations (0.65–0.79) being for a time lag of 5–7 months, i.e. for the winter following measurements. The p-tests for these time lags are also sufficiently small, from 0.02 to 0.024. Better results were obtained for correlations between the AW temperature and mean ice-free area for December, January and February (Table 2). It is characteristic

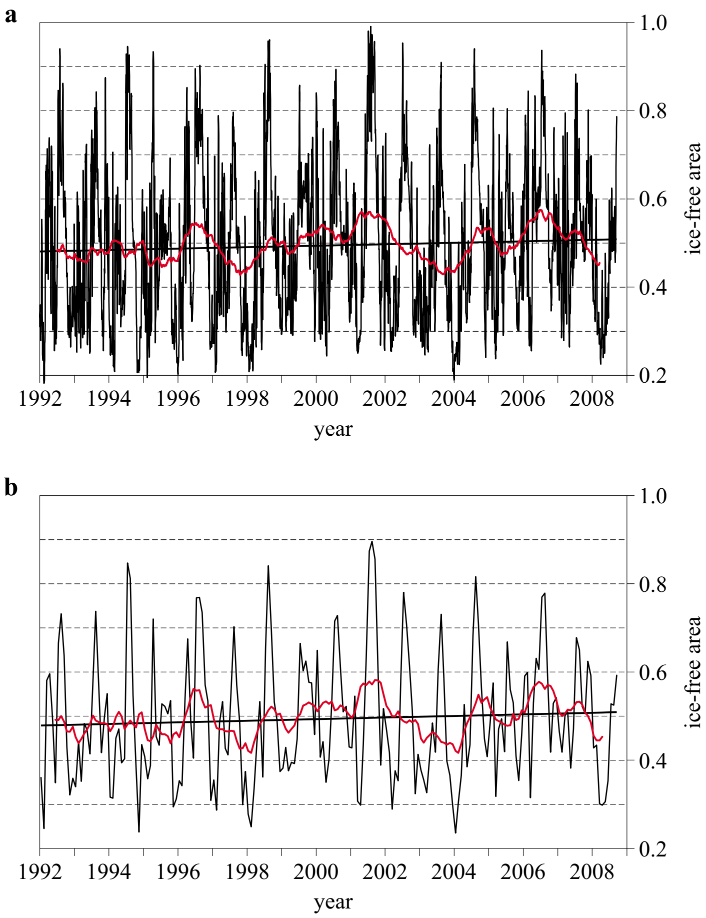

Figure 11. (a) Daily and (b) monthly mean ice-free area ratio in the study region. Linear trends (black lines) and running averages (365 days and 11 months respectively) are indicated

Table 3. Correlation coefficients and p-tests for AW temperature for the whole transect 'N', its western and eastern ends, and the sea-ice area around Svalbard in winter (December–January–February) before and after AW measurements. Detrended data

	Ice-free area, the winter before	p-test	Ice-free area, the winter after	p-test
TAW	0.40	0.2029	0.68	0.0142
TAW_east	0.55	0.0641	0.57	0.0551
TAW_west	0.45	0.1465	0.81	0.0013

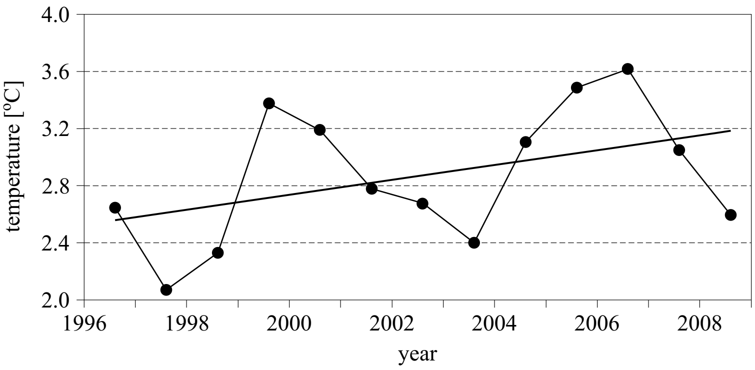

Figure 12. Time series of summer AW temperatures in transect 'N', summers 1996–2008

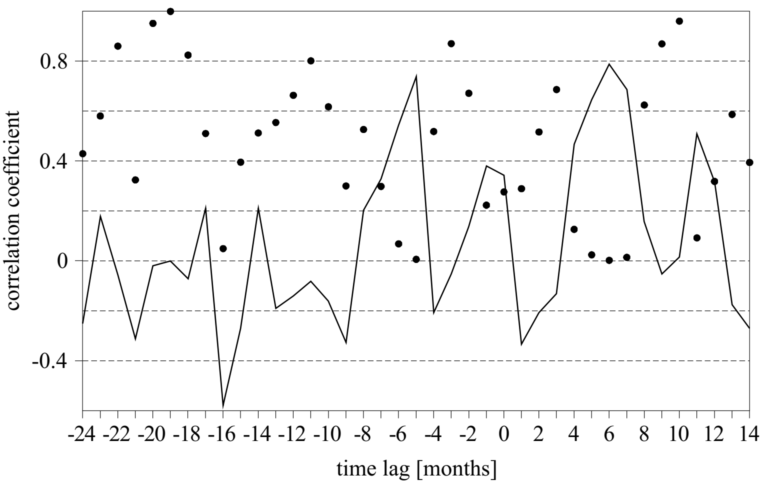

Figure 13. Correlation coefficient (solid line) between AW temperature in transect 'N' and the time-lagged ice-free surface around Svalbard, and p-test values (dots)

that the AW temperature at the western end of transect 'N' (TAW_west) correlates better than the temperature at its eastern end.

Correlations for detrended data were also calculated: they are lower, but still significant (Table 3).

4. Discussion

The results show that changes in AW temperature affect the extent of sea ice cover north and north-west of Svalbard, but the effect is not detectable during the summer. The greatest influence on ice cover occurred during the winter following the AW temperature measurements. However, the correlation of AW temperature with ice cover during the previous winter may also be high.

These results are logical. During the summer the ice cover depends on numerous factors (solar radiation, wind stress, atmospheric heat transport), and AW temperature is by no means the most important component. By contrast, oceanic heat transport is for ice melting the most important factor during the winter, and its variability correlates very well with the changes in ice cover. At first glance, the relatively high correlation between the investigated properties for the negative time lag (Figure 13) may seem strange. But the continuous process of AW advection is recorded only once a year. The temperature anomaly recorded during a particular summer could have influenced the sea ice cover six months previously. These are the effects of the ocean's 'memory' and the advective nature of oceanic heat in this region.

The second result is also important. There is a higher correlation between ice cover and AW temperature for the western branch of WSC than for the eastern one. On the one hand, this confirms our knowledge about the behaviour of AW in the Fram Strait region; on the other, it underscores the significance of the western branch of WSC (Walczowski & Piechura 2007). After passing Fram Strait, the eastern branch (WSC core, Svalbard Branch) subducts below colder, but much fresher Polar Waters. Admittedly, this branch releases large amounts of heat north of Svalbard (Cokolet et al. 2008), but most of the heat carried by this water is isolated from the ice cover and may be released in remote regions of the Arctic Ocean. Conversely, part of the water carried by the western WSC branch flows into the AO as the Yermack Branch (Manley 1995). Flowing over the shallow Yermack Plateau, AW has the greatest possibility of interacting with the sea ice around Svalbard and to melt it.

There are numerous factors shaping the Arctic Ocean ice cover. It appears that fluctuations in the heat supply from the West Spitsbergen Current and how these take place are important for AO ice conditions. Eddies are a permanent feature in the WSC, some of them being almost permanently located there. In addition, huge anticyclonic eddies, occasionally formed in the western branch of WSC, carry prodigious amounts of heat that enter the Arctic Ocean in addition to the mean inflow. This input of additional heat to the AO could be triggering rapid melting. This is particularly important nowadays, when a larger ice-free ocean surface appears in the summer. This creates good conditions for more ice production in winter, which means more brine production, more intensive deep convection and the pushing up of warm Atlantic Water from down below. Again, it makes for a greater ice-free surface in summer, more ice production in winter and so on – a kind of self-sustaining mechanism or feedback. If this were true, we could expect more and more ice-free Arctic Ocean in summer, but of course only if all other factors remained unchanged, which is hardly likely. Nevertheless, this possibility should be taken into consideration.

Acknowledgements

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References

Cokelet E. D., Tervalon N., Bellingham J. G., 2008, *Hydrography of the West Spitsbergen Current, Svalbard Branch: Autumn 2001*, J. Geophys. Res., 113, C01006, doi:10.1029/2007JC004150.

Hansen B., Østerhus S., 2000, *North Atlantic-Nordic sea exchanges*, Prog. Oceanogr., 45 (2), 109–208.

Hansen B., Østerhus S., Turrel W., Jonsson S., Valdimersson H., Hátún H., Olsen S., 2008, *The inflow of Atlantic water, heat and salt to the Nordic Seas across the Greenland-Scotland Ridge*, [in:] *Arctic-Subarctic ocean fluxes*, R. R. Dickson, I. Meincke & P. Rhines (eds.), Springer, Dordrecht, 15–43.

Jónsson S., Briem J., 2003, *Flow of Atlantic water west of Iceland and onto the north Icelandic shelf*, ICES Mar. Sci. Symp., 219, 326–328.

Manley T. O., 1995, *Branching of Atlantic Water within the Greenland-Spitsbergen Passage: an estimate of recirculation*, J. Geophys. Res., 100 (C10), 20627 –20634.

Orvik K. A., Niiler P., 2002, *Major pathways of Atlantic water in the northern North Atlantic and Nordic Seas toward Arctic*, Geophys. Res. Lett., 29 (19), 1896, L015002, doi:10.1029/2002GL015002.

Polyakov I. V., Beszczynska A., Carmack E. C., Dmitrenko I. A., Fahrbach E., Frolov I. E., Gerdes R., Hansen E., Holfort J., Ivanov V. V., Johnson M. A., Karcher M., Kauker F., Morison J., Orvik K. A., Schauer U., Simmons H. L., Skagseth Ø., Sokolov V. T., Steele M., Timokhov L. A., Walsh D., Walsh J. E., 2005, *One more step toward a warmer Arctic*, Geophys. Res. Lett., 32, L17605, doi:10.1029/2005GL023740.

Rudels B., Fredrich H. J., Quatfasel D., 1999, *The Arctic circumpolar boundary current*, Deep-Sea Res. Pt. II, 46 (6–7), 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*, R. R. Dickson, I. Meincke & P. Rhines (eds.), Springer, Dordrecht, 15–43.

Skagseth Ø., Orvik K. A., Furevik T., 2004, *Coherent variability of the Norwegian Atlantic Slope Current derived from TOPEX/ERS altimeter data*, Geophys. Res. Lett., 31, L14304, doi:10.1029/2004GL020057.

Spreen G., Kaleschke L., Heygster G., 2008, *Sea ice remote sensing using AMSR-E 89-GHz channels*, J. Geophys. Res., 113, C02S03, doi:10.1029/2005JC003384.

Walczowski W., 2009, *Woda Arktyczna w Morzach Nordyckich – właściwości, zmienność, znaczenie klimatyczne*, Rozpr. monogr. 22, Inst. Oceanol. PAN, Sopot, 241 pp.

Walczowski W., Piechura J., 2006, *New evidence of warming propagating toward the Arctic Ocean*, Geophys. Res. Lett., 33, L12601, doi:10.1029/2006GL025872.

Walczowski W., Piechura J., 2007, *Pathways of the Greenland Sea warming*, Geophys. Res. Lett., 34, L10608, doi:10.1029/2007GL029974.

Walczowski W., Piechura J., Osiński R., Wieczorek P., 2005, *The West Spitsbergen Current volume and heat transport from synoptic observations in summer*, Deep-Sea Res. Pt. I, 52 (8), 1374–1931.

Whelan J., Maslowski W., Clement Kinney J. L., Jakacki J., 2007, *Understanding recent variability in the Arctic Sea ice thickness and volume – synthesis of model results and observations*, Eos Trans. AGU, 88 (52), Fall Meet. Suppl., Abstract C22A-06.