Volume, heat and salt transport by the West Spitsbergen Current

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During the summer of 2000 (June–July) 14 CTD and ADCP transects perpendicular to the West Spitsbergen Current and along the western border of the Barents Sea were made. The measurements covered the area between 69° 43' and 80° N and 01° and 20° E. The main purpose was to follow changes in volume, heat and salt content of Atlantic Water (AW) on its way north. The strongest and most stable flow of AW was located along the continental slope where northward flowing currents exceeding 40 cm/sec were measured. A few weaker northward branches were also found to the west of the slope. South-directed currents were recorded between them and eddy-like mesoscale structures were commonly observed. Measured by vessel-mounted acoustic Doppler current profiler (VM-ADCP), the net northward transport of AW volume in the upper 136 m layer decreased from nearly 6 Sv at the southernmost transect to below 1 Sv at a latitude of 78° 50' N. Similarly, heat transport drops from about 173 TW to about 9 TW and relative salt transport (over 34.92 psu) from 980 × 10^3 kg/sec to 14 × 10^3 kg/sec. Transport in the southern direction prevails at the transect located between 79° 07' and 79° 30' N. The calculated baroclinic geostrophic transport of AW volume, heat and salt in the upper 1000 m layer behaves similarly. East-directed transport dominates at the Barents Sea boundary while westward flow prevails on the western side of the West Spitsbergen Current.

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The Greenland, Iceland and Norwegian seas play a unique role in the circulation of the world's oceans. They control the main exchange of heat and salt between the Atlantic and Arctic oceans. The principal source of heat and salt for the Arctic Ocean is the North Atlantic Ocean. Atlantic Water (AW), a surface water mass associated with a temperature and salinity maximum, enters the Norwegian Sea across the Iceland–Scotland Ridge at a temperature of 6 to 8 °C and a salinity of 35.1 to 35.3 psu (Maslowski 1994). The transport of such a large amount of heat causes the abnormally warm climate of north-west Europe and the Nordic seas. This region's climate is 5 - 10 °C warmer than the zonal mean. AW is carried to the north by the Norwegian Atlantic Current (NwAtC). This current splits into two branches. One is driven to the east as the North Cape Current enters the Barents Sea where AW is significantly modified before reaching the central Arctic (Hopkins 1991). The branch moving towards the north becomes the West Spitsbergen Current (WSC). As it approaches Fram Strait, the AW partly recirculates back into the Greenland Sea to become intermediate water with a salinity of ca. 34.9 to 35.0 psu and a temperature of about

0 °C to 2 °C. The remaining part of AW enters the Arctic Ocean through Fram Strait.

When AW leaves the Nordic seas through Fram Strait it has a salinity of about 35.0 psu and its temperature is about 5 °C lower than it was upon entry (Maslowski 1994).

Until the 1970s, the only measurements of the NwAtC and WSC were CTD observations and transport was estimated assuming geostrophy. The first current meters were deployed in Fram Strait over the Spitsbergen continental slope (Aagaard et al. 1973). The results show a strong barotropic component in the measured currents. Estimates of volume transport for the WSC are summarized in Table 1. The best and the most complete current measurements were recently carried out within the scope of the VEINS project, but the data are still being processed.

In recent years, oceanographers have begun using a revolutionary current meter, the acoustic Doppler current profiler (ADCP), which, together with GPS, provides quasi-continuous measurements of currents along ship routes. Unfortunately, due to technical problems there are not many papers based on vessel-mounted ADCP measurements in the Nordic seas. Vessel- mounted ADCP (VM-ADCP) data were analysed for measurements in the Arctic Frontal Zone in the Greenland Sea (van Aken et al. 1995), in the Barents Sea Polar Front (Gawarkiewicz & Plueddemann 1995; Parsons et al. 1996) and the Barents Sea opening (Haugan 1999), as well as for the Svinoy section in the Norwegian Sea (Orvik et al. 2000). To the best of our knowledge, this is the first publication using VM-ADCP data in the WSC region.

The aim of this presentation is to describe changes in volume, heat and salt content of AW on its way from the northern coast of Norway up to Fram Strait. Some results of studies on flow dynamics and structure are also presented.

VM-ADCP data

Throughout the cruise, the 150-kHz BB-VM ADCP (RD Instruments, San Diego) mounted in the hull of R/V *Oceania* was used to obtain vertical profiles of current speed and direction in the upper layer. The ADCP reached the maximum depth of measured currents at about 400 m, but due to quality control, it was reduced to only 150 m. The ADCP measurements do not comprise the sea surface, in our case the 0 - 16 m layer. The depth bin length was set to 8 m. The ADCP data were averaged in 5 minute ensembles equivalent to 0.75 km horizontally at a speed of 5 knots. These settings produce a random error in the horizontal velocity component of about 0.95 cm/sec (RD Instruments 1989). Current measurements included in calculations were collected when the ship sailed at speeds from 4 to 6 knots and with no change in direction. The minimum percentage of good pings in the ensemble was set to 75 and the error velocity was set at 10 cm/sec.

Most of the measurements were done in regions where depth is greater than the range of the ADCP bottom-track (ca. 500 m) so we had to rely on navigation as a reference. In this case, the crucial parameter for data quality is the misalignment angle. To solve this problem, transects were run partly in the shelf region where bottom-track and navigation reference were available and this allowed us to calculate the misalignment angle. The procedure was repeated for each transect (Osiński 2000).

At the moment the ADCP data are not detided. However, the tides cannot be completely discarded. Measurements during VEINS revealed tidal currents up to 7 - 10 cm/sec on the West Spitsbergen slope (Woodgate et al. 1998). Tidal velocities are considerably lower in deep regions and do not produce significant error in ADCP data there, although they are an unknown contribution to the measured flow field.

Hydrographic data

Between 23 June and 14 July, fourteen CTD transects were performed, comprising an area between 69° 43’ and 80° N and 01° and 20° E (Fig. 1). More dense coverage was carried out in the Sørkapp region and along the north-western part of the Svalbard shelf. Data were collected using a Seabird 9/11+ CTD probe.

Results

The broad flow of AW, over 300 miles wide at the southernmost section, narrows on its way northward to less than 100 miles (Fig. 1). The very narrow flow of AW at 75° N is caused by both strong cyclonic and anticyclonic eddies. The core of the AW is situated at a depth of about 100 m on average (Fig. 2). On the western side of the stream and in the cyclonic eddies around Bjørnøya (Bear Island) and Sørkapp, the core is found at a depth of ca. 50 - 60 m. In the centres of anticyclonic gyres it is pushed down to a depth of more than 200 m, reaching a maximum depth of nearly 300 m at 76° N, 13° 40' E. This very strong anticyclonic eddy, together with the intensive cyclonic one to the west of Sørkapp, results in large horizontal gradients of temperature and salinity and significant baroclinic transport to the south-east.

The maximum temperatures in the core of AW are observed in the upper layer of ca 40 m, reaching about 8 - 9 °C in the south and decreasing slowly to about 6 °C at the entry to Fram Strait. That means this water was a bit warmer than usual. A similar tendency is discernible in temperature distribution at the 100 m depth (Fig. 1); however, its horizontal gradient towards the north is less than in the upper layer. Maximum salinity found in the AW drops very little, from about 35.2 to 35.11 psu, in the same area. The depth of maximum salinity along the main stream of AW (Fig. 2) is perceptibly disturbed by meanders and eddy-like structures. AW occupies most of the passage between Norway and Bjørnøya and part of the Bjørnøya–Sørkapp opening, namely the Storfjordrenna.

ADCP data (Fig. 3) generally confirm circulation patterns already indicated by T, S distributions (Figs. 1 and 2). There are signs of many eddy-like features, both cyclonic and anticyclonic, which result in frequent current direction reversal and opposite flows across the measured sections. The strongest currents were observed along the continental slope (Fig. 4) and a speed of over 40 cm/sec was recorded in the surface layer. The second area of high current speeds is located in the close vicinity of ridges and the fracture zone. In the area of 73° to 73° 30' N and 05° to 08° E, strong currents cross Mohn's Ridge and exit the research area to the west. These waters probably come back to the research area farther north between 75° and 76° 30' N. This could be the reason why at the more northern transect N (76° 30' N) transport is significantly higher than that found farther to the south at transect KK (75° N; Fig. 5, Table 2). The fact that properties of water at the westernmost stations of transect HH and N are similar seems to confirm this assumption. Strong currents were measured in the northern part of the Svalbard shelf, where Knipovich Ridge comes close to the continental slope and the deep area narrows. To the north of Knipovich Ridge currents turn to the west and even partly back to the south. At the northernmost transect in Fram Strait, splitting of the main stream into two separate branches is apparent: one branch of the WSC turns right and another one turns left. Accordingly to Manley (1995), the former stream represents the Svalbard branch, the largest influx of AW into the Arctic Ocean, and the latter one can be identified as the Yermak branch. When comparing currents at 50, 100 and 150 m depths, one can see that the circulation pattern is preserved at all these depths. Current speed decreases but only in the southern part, while north of 76° high values are maintained as well.

The volume transports in the 136 m surface layer (depth from 16.2 m up to 152.2 m) calculated from ADCP data (Fig. 5) show a decrease in the northward transport from over 7 Sv in the south to about 1 Sv in the north; the south-directed transport behaves similarly. There are also some exceptions, for example, the increase of northward transport between 75° and 76° 30' N. As mentioned earlier, some additional inflows from the west could occur. Another explanation could be that the transect along 75° N is too short in the western direction and does not catch all the transport to the north. The increase of south-

Table 1. West Spitsbergen Current transport estimates by various researchers.

Author	Transport (Sv)	Remarks
Leonov (1947)	2.5	78° N section
Hill & Lee (1957)	1.1 (3.2 max.)	74° 30' N upper 400 m with 750 dB reference (1949–1956)
Kislyakov (1962)	3.2 ± 1.5; 0.5 min. summer/ 5.5 max. winter	74° 30' N section with 1000 dB reference (1954–59)
Timofeyev (1962)	3.1 ± 0.6	78° N section with 1000 dB reference from annual estimates 1933–1960
Aagaard et al. (1973)	8.0	79° N using current meter data 1971–72 and hydrography
Hanzlick (1983)	5.6; 11.9 max. Dec./ 1.4 min. March	79° N using current meter data 1976–77 and hydrography

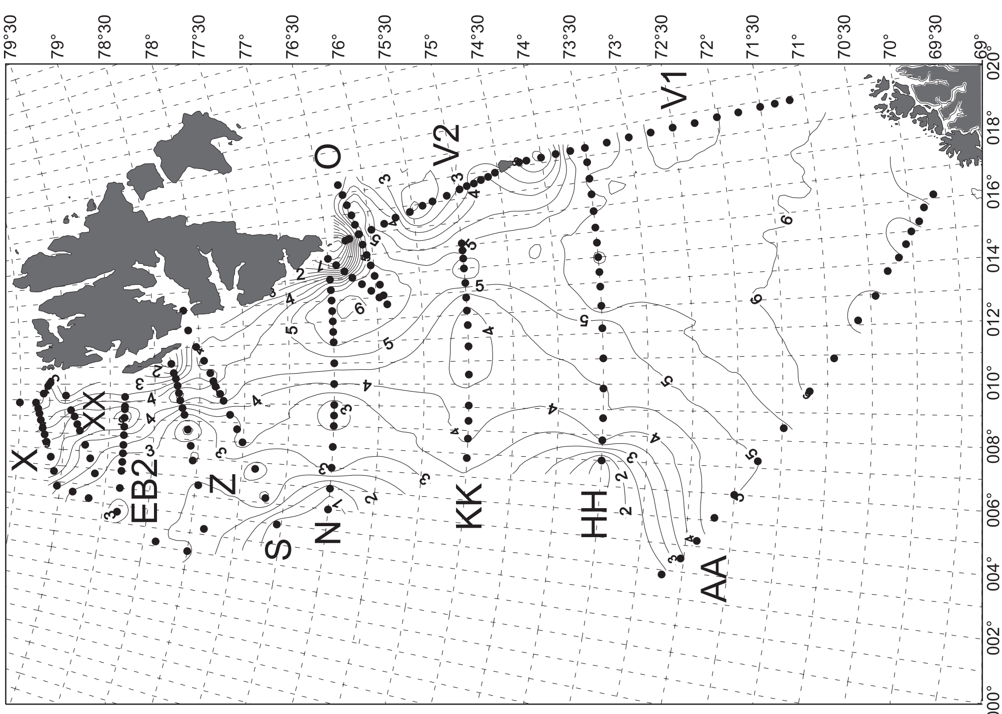

Fig. 1. Horizontal distribution of potential temperature at the depth of 100 m.

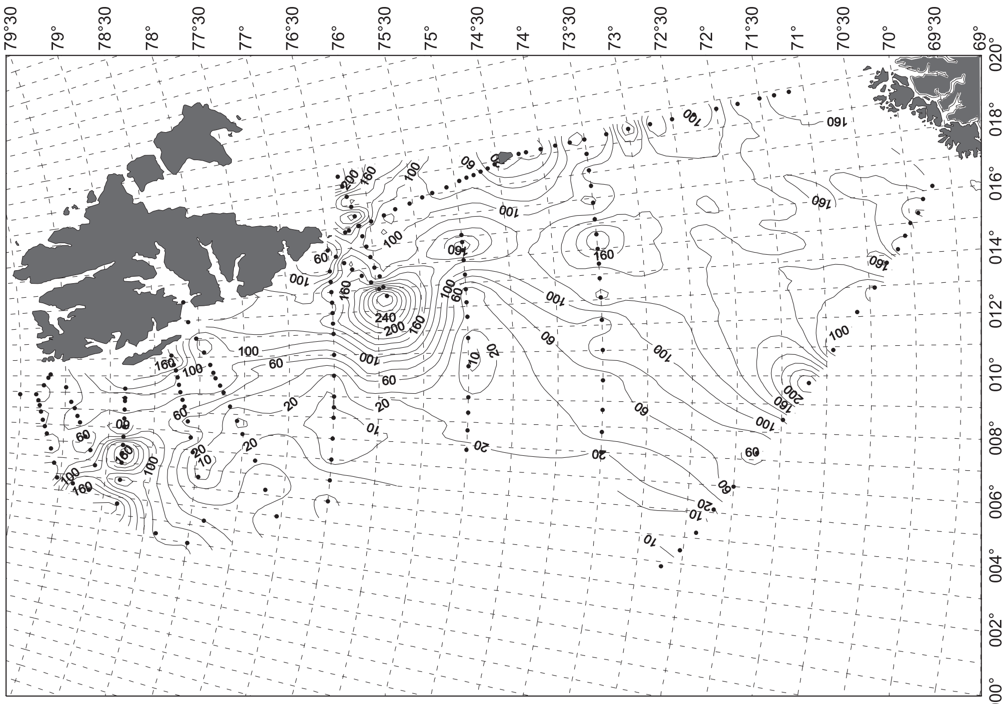

Fig. 2. Horizontal distribution of the maximum salinity depth.

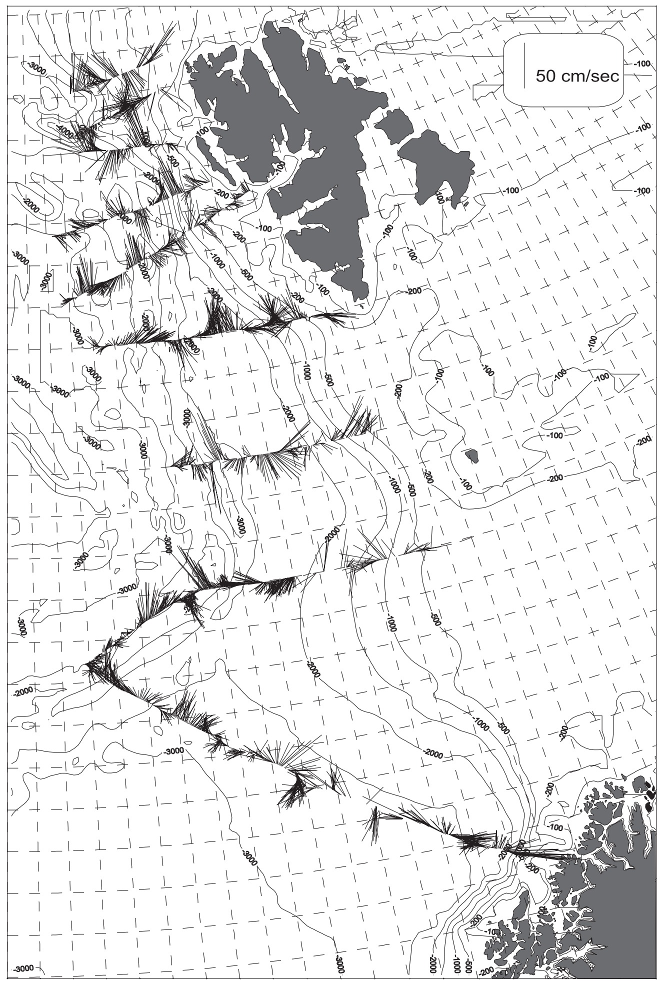

Fig. 3. Current sticks at 50 m level.

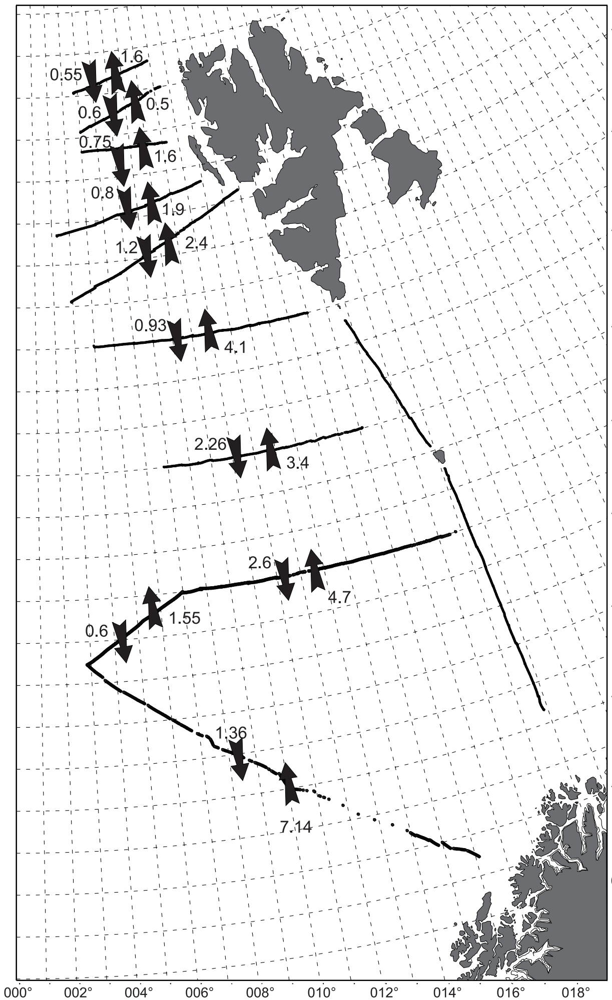

Fig. 5. Northward and southward ADCP measured transport across transects.

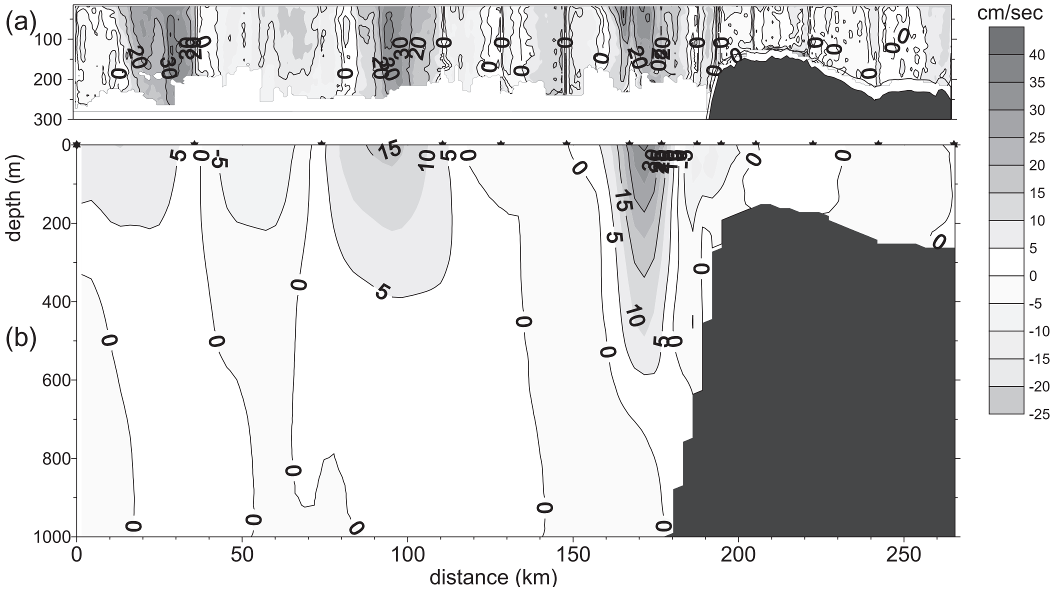

Fig. 4. (a) Vertical distributions of the perpendicular component of ADCP measured current, and (b) calculated baroclinic geostrophic current with reference level 1000 m at transect S.

bound transport at the mouth of Isfjord could be caused by freshwater outflow from that fiord.

The calculated baroclinic geostrophic currents above a 1000 db reference level reveal alternatively changing directions in most sections. This fact confirms the important role of the mesoscale eddy-like structures travelling with the main flow of AW to the north. The strongest baroclinic forcing occurred along the continental slope where the main branch of AW can be found (Fig. 4).

Table 2. ADCP measured transport across transects.

		Total area of transect (16.2 - 150.2 m)					Part of transect occupied by AW (salinity >34.92 psu)			
Transect	Transect latitude	Transect length (km)	Volume transport (Sv)	Heat transport (TW)	Total salt transport (10^3 kg/sec)	Relative salt transport Sref = 34.92 psu (10^3 kg/sec)	Volume transport (Sv)	Heat transport (TW)	Total salt transport (10^3 kg/sec)	Relative salt transport Sref = 34.92 psu (10^3 kg/sec)
(Positive values = northward transport; negative values = southward transport)										
AA	69° 43' - 72° 44' N	583.08	5.58	172.9	217188.4	982.5	5.74	173	217339.1	977.6
HH	73° 30'N	371.13	2.1	49.42	74649.2	286.6	2.04	45.8	68743.5	316.6
KK	75° N	266.75	1.14	40.2	58192.9	266.7	1.03	39.9	57839	275.5
N	76° 30' N	285.50	3.17	56.4	97646.2	333.2	3.07	54	94494.7	397.4
S	77°03' - 78° 10' N	290.28	1.1	14.77	30619.5	13.9	0.9	12.9	24491.4	96.4
Z	77° 51' - 78° 19' N	209.13	1.2	12.2	29546.2	12.3	0.72	10.7	21034.2	78.9
EB2	78° 50' N	113.36	0.85	8.05	17357.1	10.4	0.95	8.9	17357.1	14.1
XX	79° 07' - 79° 30' N	103.16	-0.1	-1.85	-4349.3	-4.4	-0.09	-2.01	-3912.5	-4.01
X	79° 32' - 79° 50' N	136.95	1.04	19.4	40094.4	108.8	0.98	18.25	37826.1	109.5

The calculated current speed varied there from 15 - 20 cm/sec in the south to 30 - 40 cm/sec in the north. The second strongest branch of AW was located mostly along the ridges on the western side of our transects. It is also possible that this stream belongs to an edge of the Greenland Gyre and therefore should be treated not as a real northward transport of AW but as a part of recirculation. Modelling mass balances of the Arctic Ocean (Rudels 1987) revealed that 50 % of all AW in Fram Strait recirculates to the south. The observed main stream can be recognized as the Svalbard branch, which is the major source of AW into the Arctic Ocean, yet because of recirculation it represents only one third of the total AW supply north of 76° (after Manley 1995). Exceptionally weak baroclinic currents and transport were observed on the Barents Sea side and in particular between Norway and Bjørnøya. The calculated speed of baroclinic currents was not higher than 5 - 10 cm/sec. Barotropic forces most probably dominated there. Similar values were obtained at the Bjørnøya–Sørkapp section, except for the area immediately adjacent to Sørkapp, where the estimated current speed exceeded 30 cm/sec.

The calculated volume, heat and salt transport of AW is presented in Table 3. It represents baroclinic geostrophic transport, which results from the flow component driven by horizontal density gradients and relative to the reference level of 1000 m. The net baroclinic transport of AW toward the north decreases from about 7 Sv in the south to about 2 Sv at the northern transects. At the northernmost section (79° 50' N), the net transport is directed to the south-east.

Similarly, the amount of heat transported by AW drops from ca. 130 TW to ca. 30 TW; therefore, about 100 TW is lost to the atmosphere, the Barents Sea and surrounding waters. Heat lost in the area to the west of Svalbard is about 85 Wm^{-2}, which is a significantly lower value than during the wintertime (Boyd & D'Asaro 1994). Relative salt transport (waters with salinity higher than surrounding waters 34.92 psu) also decreases about five-fold from more than 1000×10^3 kg/sec to ca. 200×10^3 kg/sec. Corresponding data for the Barents Sea border indicate a very small baroclinic

Table 3. Calculated geostrophic baroclinic transport across measured transects with the reference level of 1000 m.

		Total area of transect (upper 1000 db)					Part of transect occupied by AW (salinity >34.92 psu)			
Transect	Transect latitude	Transect length (km)	Volume transport (Sv)	Heat transport (TW)	Total salt transport (10^3 kg/sec)	Relative salt transport Sref = 34.92 psu (10^3 kg/sec)	Volume transport (Sv)	Heat transport (TW)	Total salt transport (10^3 kg/sec)	Relative salt transport Sref = 34.92 psu (10^3 kg/sec)
(Positive values = northward transport; negative values = southward transport)										
AA	69° 43' - 72° 44' N	583.08	7.59	133.06	273257.4	1063.0	6.87	127.63	247540.2	1084.4
HH	73° 30'N	371.13	4.27	61.83	153710.8	480.7	3.77	61.79	135659.8	489.3
KK	75° N	266.75	4.80	76.48	172796.5	653.2	4.56	78.88	164198.4	639.7
N	76° 30' N	285.50	2.47	32.76	88884.8	257.4	2.25	33.12	81142.6	253.6
S	77°03' - 78° 10' N	290.28	2.90	36.36	104208.5	265.5	2.62	36.69	94124.4	285.2
Z	77° 51' - 78° 19' N	209.13	1.73	29.502	62201.2	250.2	1.90	29.73	68435.5	222.0
EB2	78° 50' N	113.36	2.24	32.447	80693.5	206.4	2.10	28.92	75412.3	228.2
XX	79° 07' - 79° 30' N	103.16	1.93	31.651	69568.6	229.3	1.99	31.86	71655.5	222.2
X	79° 32' - 79° 50' N	136.95	-1.09	-13.533	-39079.5	-32.8	-0.93	-12.59	-33491.9	-64.5
(Positive values = eastward transport; negative values = westward transport)										
V1	71° 10' - 74° 15' N	343.93	0.82	18.83	29657.6	64.5	0.72	16.05	25897.0	71.0
V2	74° 32' - 76° 17' N	204.01	0.58	5.237	20556.1	-131.8	0.10	0.93	3713.7	3.5

geostrophic transport of volume (below 1 Sv), heat (16×10^{12} W) and salt (71×10^3 kg/sec) to the east. Calculations for section U, bordering the measured area on the western side and running from 78° to 79° 30' N and 01° to 03° 45' E, reveal that westward baroclinic transport is equal to 1.3 Sv volume, about 12 TW heat and 80×10^3 kg/sec salt.

Summary

The movement of the whole system along the continental slope was observed. The calculated baroclinic geostrophic currents, as well as those measured by the ship-mounted ADCP, confirm the existence of numerous mesoscale cyclonic and anticyclonic eddies in the main stream of the WSC. The baroclinic transport (upper 1000 m) and total transport measured by VM-ADCP (16 - 152 m) are of the same order, suggesting that barotropic component of the flow prevails in the upper layer. The first results confirm this supposition. The ADCP measurements allow us to calculate absolute geostrophic velocities (ADCP-referenced) and total (baroclinic plus barotropic) transport. To obtain a profile of absolute geostrophic velocity, mean vertical (50 - 150 m layer) and horizontal (between two CTD stations) ADCP measured perpendicular to transect component of velocity and vertical mean calculated baroclinic velocity for the same layer were compared. The difference was treated as the barotropic component. This method was used and described in detail by Meinen et. al. (2000) and Colelet et al. (1996). The calculations made for deep transects N, S and Z (see Fig. 1) show that the total ADCP-referenced transport in the whole water column is two to three times higher than the baroclinic one referenced to the level of 1000 m. These calculations will be published soon in separate paper.

The northward flow of AW carries a huge amount of heat and salt to the high latitudes; on its way from northern shores of Norway to Fram Strait it loses about 100 TW of heat and 800×10^3 kg/sec of salt.

Results obtained thus far are preliminary; the data are very fresh and require further processing.

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