Papers

Heat and salt fluxes in the West Spitsbergen Current area in summer

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Abstract

Fluxes of radiation, sensible and latent heat, and fluxes of heat and salt within the upper layer of the ocean were calculated on the basis of measurements carried out in the area of the Norwegian-Atlantic and West Spitsbergen Currents during summer 2000.

The sea surface radiation balance was calculated from direct measurements of downward and upward short-wave (solar) radiation, the net radiation fluxes and sea surface temperature. The daily doses of radiation energy reaching and leaving the sea surface were also estimated.

To calculate the vertical heat fluxes in the atmospheric boundary layer the bulk parameterisation method was used. In most cases, the calculated heat fluxes were rather low, the average sensible heat flux was c. 10 W m^{-2}, and the latent heat flux about one order of magnitude higher; this is what could be expected in summer. Salt fluxes to the air in the process of aerosol production are very small and can be neglected.

In summer the highest quantities of heat and salt are exchanged during mixing with surrounding waters.

According to our measurements, Atlantic Water on its northward course from about 70°N to 79°N loses about 100 TW of heat and 900×10^3 kg of salt. We thought it could be interesting to find out what happens to them. Some preliminary results of our investigation are presented here.

1. Introduction

The Greenland, Iceland and Norwegian (GIN) Seas constitute a very important region as regards the world's ocean circulation and hence the Earth's climate system. The GIN Seas contain anomalously warm water for their latitude as a result of advective heat transport by the Norwegian Atlantic Current (NAC) and subsequently by the West Spitsbergen Current (WSC), which carries warm, saline Atlantic Water (AW) (Haugan 1999). This region is the northernmost, permanently ice-free oceanic area on the Earth. The area of maximum heat loss is situated to the east and south of Spitsbergen (Häkkinen & Cavalieri 1989, Simonsen & Haugan 1997).

The exchange of radiation energy between the atmosphere and the ocean or land surface has a considerable influence on the Earth's climate (Trenberth 1992). The net short- and long-wave radiation fluxes are a component of the total radiation budget of the ocean or sea surface. The radiation flux is the difference between incoming and departing sea surface solar and infrared radiation. Long-wave radiation fluxes depend on many physical parameters of the atmosphere and the sea, but to describe these complicated relationships precisely in a straightforward manner is no easy task. Nevertheless, the literature gives a number of practical algorithms for estimating the net long-wave radiation flux for climate modelling purposes (e.g. Fung et al. 1984 and the papers cited there, Bignami et al. 1995, Zapadka et al. 2001; see also Timofeyev 1983, Trenberth 1992). They all assume that the sea (or Earth's surface) radiates in almost the same way as a black body according to the Stefan-Boltzmann law (with a total emissivity of almost one). Hence, only the sea surface temperature T_s is needed to describe the flux. To describe the long-wave flux from atmospheric data, empirical formulae are applied which are generally functions of the temperatures of the air T_a and sea surface T_s, the surface water vapour pressure e_a, and the cloudiness C. These four easily measurable physical quantities are used to parameterise the long-wave radiation flux because they are readily obtained from standard meteorological observation data sets.

Calculations of sensible and latent heat fluxes in the Arctic were given by Romanov et al. (1987). Similar research was done at the Institute of Oceanology in the early nineties by Jankowski (1991) and Druet (1993). Our calculations were based on measurements of meteorological parameters made during the r/v 'Oceania' cruise in 2000.

In spite of the importance of WSC, there are very few consistent estimates of the volume transport and heat fluxes because of the complexity of its flow structure (Hopkins 1991). Only recently, thanks to new developments in measuring techniques, have the opportunities to do this radically improved. The Acoustic Doppler Current Profiler (ADCP) mounted on board ship is a completely different way of estimating transport. As a result, quasi-continuous measurements along the ship's course provide much better information than can be obtained from chains of mechanical current meters, whose spatial resolution is poor. The resolution is especially important as regards WSC, which is a flow displaying considerable complexity, especially beyond the continental slope (Piechura et al. 2001, Saloranta & Haugan 2001).

The main objective of the present paper was to calculate fluxes of heat and salt carried by Atlantic Water within the West Spitsbergen Current (WSC) along the continental shelf of western Spitsbergen.

2. Data and methods

The data on which this paper is based were collected during June–July 2000 by r/v 'Oceania' in the Norwegian, Greenland and Barents Seas.

Downward and upward short-wave (solar) radiation fluxes and the net radiation flux (combined solar and terrestrial radiation) were measured directly with Kipp & Zonen CM6B pyranometers, a Campbell Sc. SP1110 pyranometer, and an R7 net radiometer. The long-wave downward and upward fluxes were estimated from the sea-surface temperature and the Stefan-Boltzmann law on the underlying assumption that the sum of all four individual fluxes yields the net radiation flux.

The sensible and latent heat fluxes were calculated using the bulk parameterisation method:

$Q_h = -\rho c_p C_H U_Z (T_z - T_0)$ – sensible heat flux,

$Q_E = -L C_E U_Z (q_z - q_0)$ – latent heat flux,

where

ρ – air density,

c_p – specific heat of air,

L – latent heat of evaporation,

U_Z, T_z, q_z – wind velocity, air temperature, absolute humidity at z level, respectively,

T_0, q_0 – air temperature, absolute humidity at sea level,

C_H, C_E – exchange coefficients of heat and humidity.

The coefficient of vapour exchange (C_E) was taken from Smith (1989) and the coefficient of heat exchange (C_H) from Panin (1985).

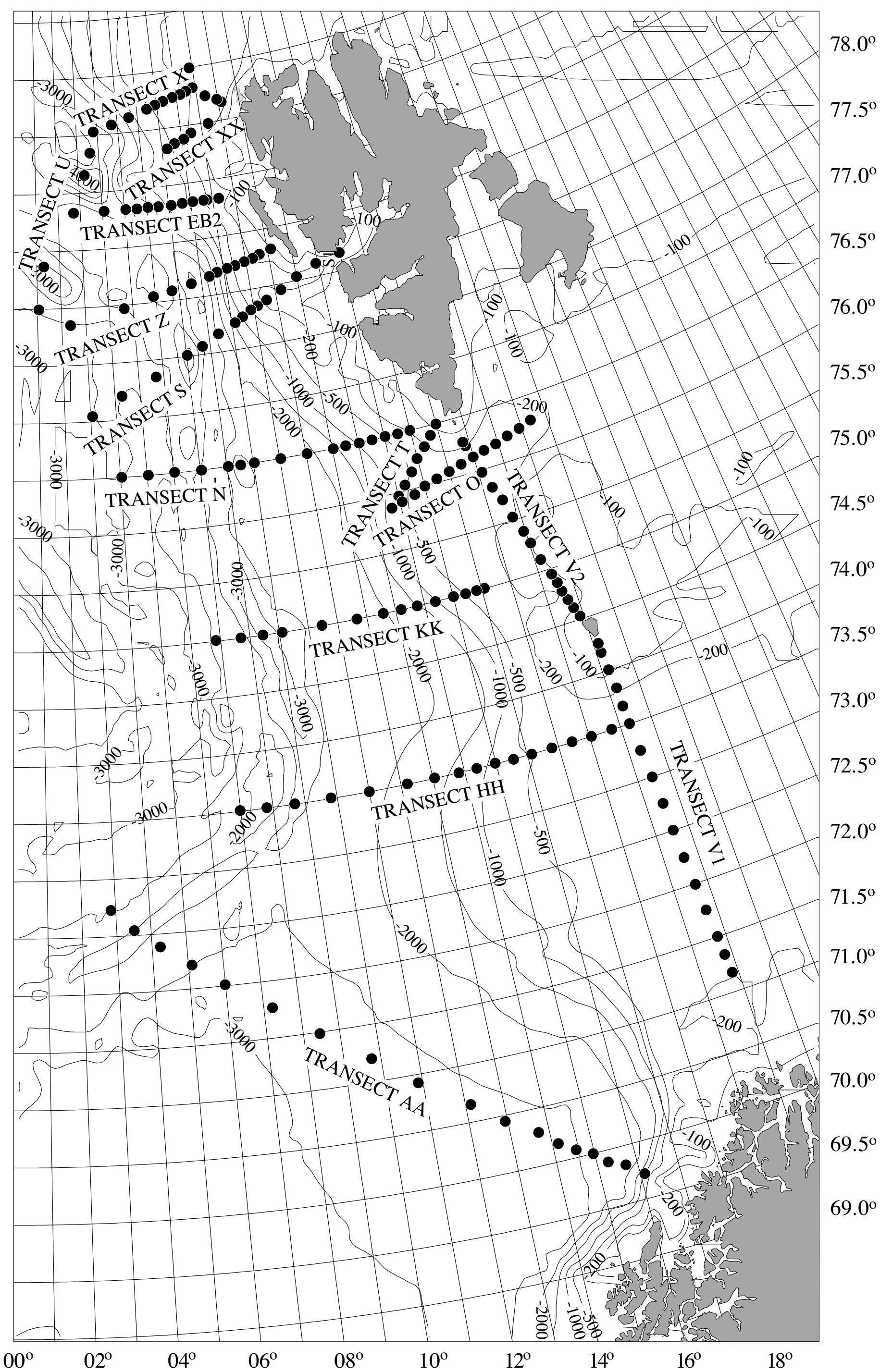

Fig. 1. Station grid and location of transects during Arex 2000

Basic meteorological parameters according to the SHIP standard were measured every 3 hours and at each CTD station.

Water temperature and salinity were recorded with a Sea Bird 9/11 + CTD probe and currents were measured with a 150–kH BB–VM ADCP (RD Instruments, San Diego) mounted in the hull of r/v 'Oceania'.

The grid of stations covered by r/v 'Oceania' in summer 2000 is shown on Fig. 1.

Calculations of volume, heat and salt transport were based on ship-mounted ADCP measurements in the upper 150 m layer (total transport) and the hydrographic data from the whole water column from surface to bottom (baroclinic component). From these, the ADCP-referenced current velocities and transport were calculated. Since Atlantic Water occupies only the top 500–700 m layer, all the results for the top 1000 m were taken into account.

3. Results

The average daily short-wave radiation energy flux reaching the sea surface, equal to about 140 W m^{-2}, was almost entirely absorbed by the sea, and only about 10 W m^{-2} was transmitted back into the atmosphere (Table 1).

Table 1. Average daily radiation fluxes at the sea surface, air and sea temperatures, and cloudiness during the AREX 2000 expedition

No.	Date	*SW*↓	*SW*↑	*SW*↓↑	*LW*↓	*LW*↑	*LW* ↓↑	NET	T_s	T_a	N
		[W m^{-2}]							[deg]		[octas]
1	24.06	160.8	9.5	151.2	325.5	343.8	–18.3	**132.9**	7.2	6.5	8
2	25.06	120.2	7.5	112.7	324.6	340.2	–15.6	**97.0**	6.5	5.0	8
3	26.06	180.8	14.4	166.4	314.3	333.8	–19.5	**146.9**	5.1	4.9	7
4	29.06	147.8	10.0	137.8	327.6	337.6	–9.9	**127.9**	6.0	5.2	8
5	30.06	103.8	6.4	97.4	324.1	340.0	–15.9	**81.4**	6.5	5.5	8
6	1.07	191.8	11.9	179.9	294.7	330.4	–35.7	**144.2**	4.5	2.8	7
7	3.07	108.1	6.3	101.8	306.0	329.3	–23.3	**78.5**	4.2	2.6	8
8	4.07	163.3	9.8	153.6	297.8	323.0	–25.2	**128.4**	2.9	1.3	8
9	5.07	157.1	9.8	147.3	311.6	334.5	–23.0	**124.3**	5.3	3.6	8
10	6.07	161.9	11.6	150.3	305.1	336.7	–31.6	**118.7**	5.8	4.0	7
11	7.07	82.1	5.4	76.7	320.6	335.5	–14.9	**61.9**	5.5	4.7	8
12	9.07	100.7	6.1	94.6	318.1	331.8	–13.7	**80.9**	4.8	4.8	8
13	10.07	187.1	14.5	172.5	300.8	336.4	–35.6	**136.9**	5.7	5.8	8
mean value		**143.5**	**9.5**	**134.0**	**313.2**	**334.9**	**–21.7**	**112.3**	**5.4**	**4.4**	**8**

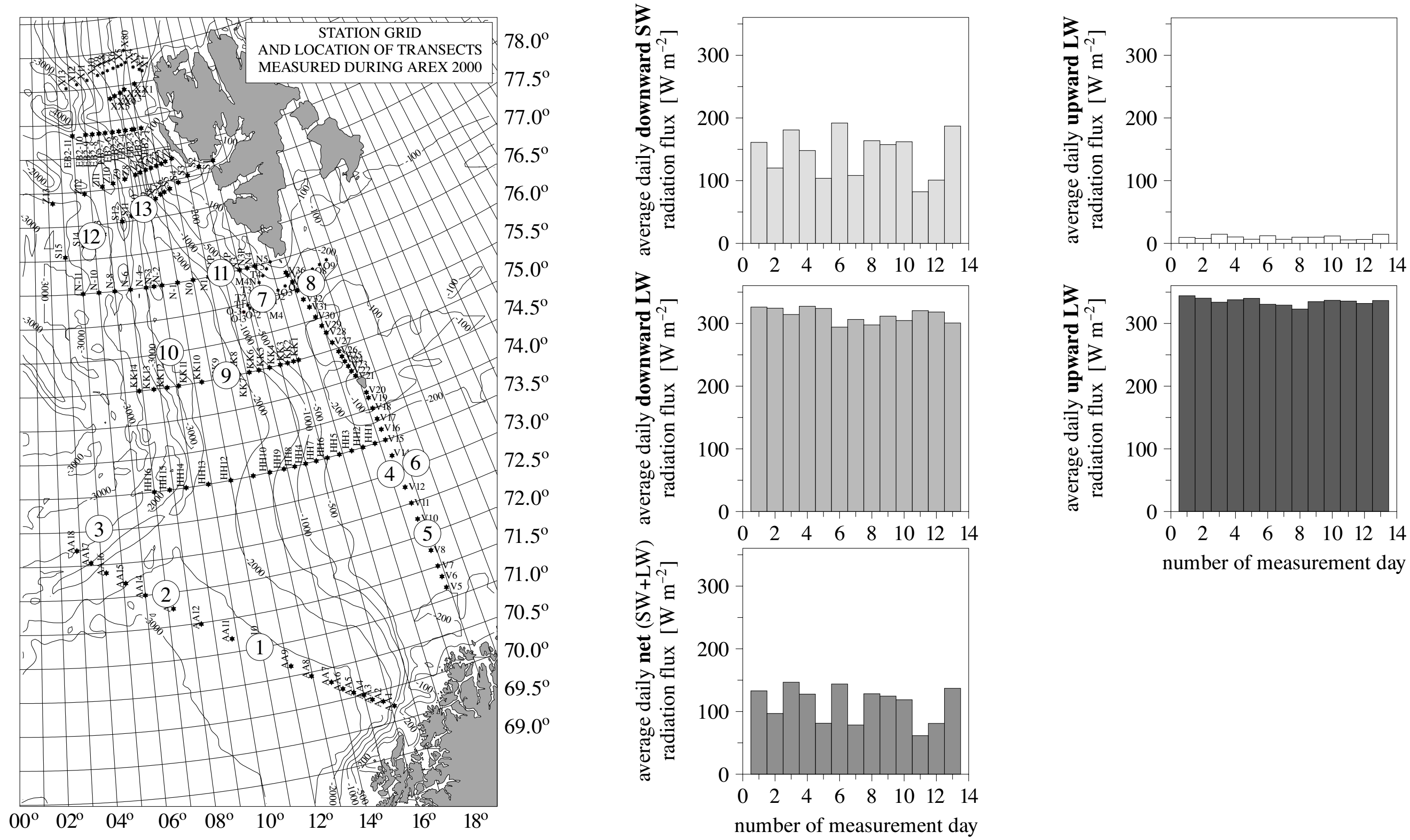

Fig. 2. Average daily radiation fluxes during Arex 2000

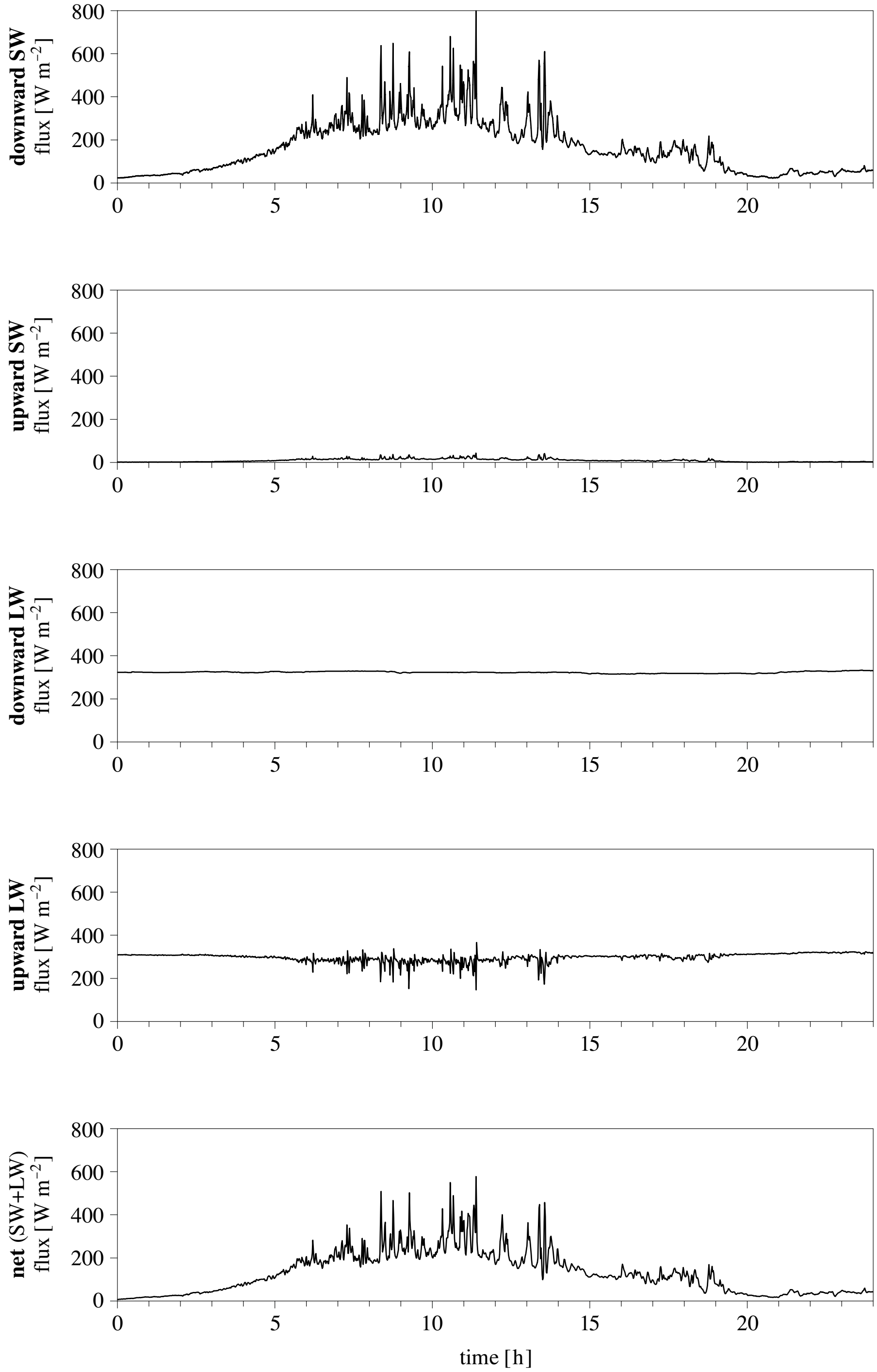

Fig. 3. Radiation fluxes for a selected day (04.07.2000)

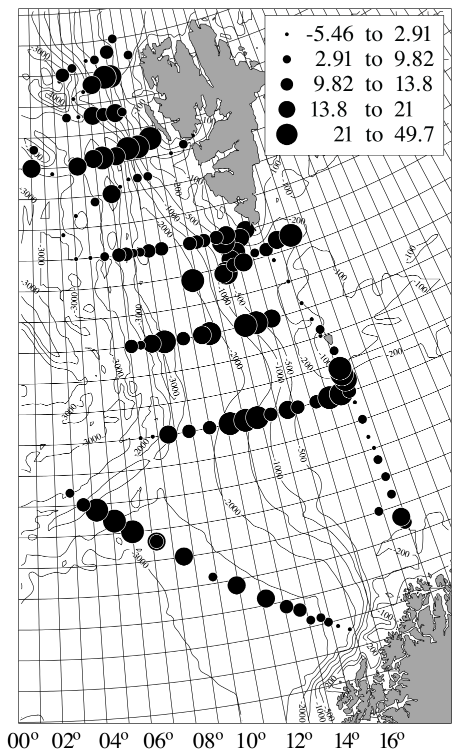

Fig. 4a. Sensible heat flux [W m^{-2}]

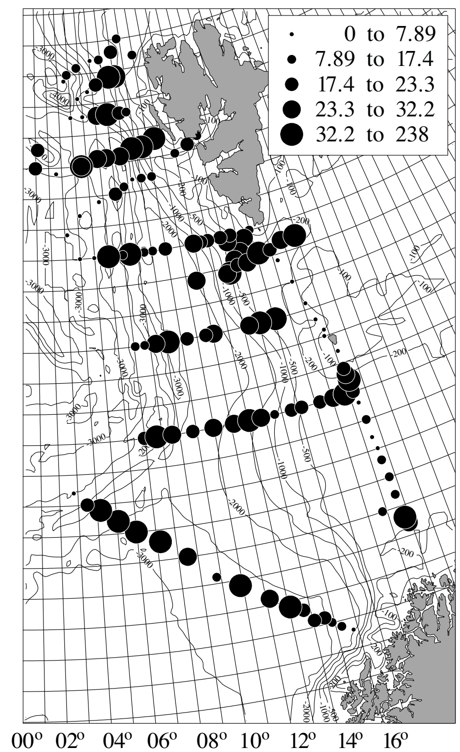

Fig. 4b. Latent heat flux [W m^{-2}]

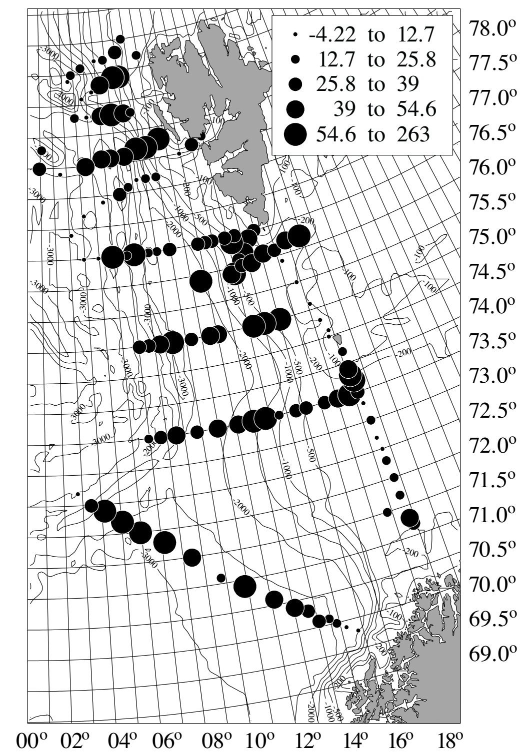

Fig. 4c. Heat flux (latent and sensible) [W m^{-2}]

In the long-wave part of the spectrum the opposite occurs: re-emission of radiation energy by the sea surface (335 W m^{-2} on average) exceeds that arriving from a cloudy sky (315 W m^{-2} on average) by about 20 W m^{-2} (Figs. 2, 3).

Radiation fluxes were measured under very uniform conditions with respect to cloud cover: this was 8 octas on 10 of the 13 measurement days, and 7 octas on the other 3. The results can therefore be regarded as typical of summer when the sky is completely overcast.

Calculated sensible heat fluxes varied from –14 W m^{-2} (sea surface gaining heat) to + 49.6 W m^{-2}, the average being c. 12 W m^{-2} (Fig. 4a). The average latent heat flux was 26 W m^{-2}, with extreme values ranging from 0 to 246 W m^{-2} (Fig. 4b). Hence, evaporation and turbulent exchange were responsible for c. 38 W m^{-2} being transmitted from the sea surface to the atmosphere in summer (Fig. 4c).

Volume, heat and salt transport, and heat fluxes across several transects from 69°30′N to 79°30′N are presented in Table 2.

Table 2. Horizontal heat fluxes and total heat fluxes into surrounding waters. All calculations done for the 0–1000 m layer

Transect	ADCP-referenced volume transport [Sv]	Heat transport [TW]	Salt transport [$10^3 \times$ kg s^{-1}]
X	5.8 ± 0.9	64 ± 10	319 ± 49
EB2	5 ± 0.9	52 ± 9	325 ± 83
Z	4.3 ± 1.7	45 ± 18	293 ± 115
S	5.3 ± 1.9	29 ± 10	169 ± 60
N	8.2 ± 2.4	110 ± 32	794 ± 232
HH	6.9 ± 2.8	137 ± 55	1006 ± 408
AA	11 ± 5.9	177 ± 94	1682 ± 902

Atlantic Water (S > 34.92, $T > 2°C$)

Transect	ADCP-referenced volume transport [Sv]	Heat transport [TW]	Salt transport [$10^3 \times$ kg s^{-1}]
X	3.6 ± 0.5	58 ± 8	429 ± 59
EB2	2.8 ± 0.4	45 ± 6	341 ± 48
Z	2.6 ± 0.3	43 ± 5	303 ± 35
S	2 ± 0.6	33 ± 12	221 ± 66
N	5.8 ± 0.9	100 ± 15	807 ± 125
HH	6.5 ± 1.6	136 ± 33	1009 ± 248
AA	9.2 ± 5.6	173 ± 105	1689 ± 1028

The volume of Atlantic Water (S > 34.92 PSU, $T > 2°$C) generally decreases from c. 9 Sv in the south (about 69°30′–72°N) to c. 2–2.5 Sv at 77–78°N, and increases to 3–3.5 Sv close to Fram Strait. These fluctuations determine the variations in the amounts of heat and salt transported by AW. The heat transport decreases from over 170 TW in the south to 33–43 TW at 77–78°N, and increases again to 45–60 TW in the northernmost area. Similarly, salt transport decreases from nearly 1700 $\times 10^3$ kg s^{-1} to 220–300 $\times 10^3$ kg s^{-1} and then rises to 430 $\times 10^3$ kg s^{-1}.

4. Discussion

In summer, the sea surface of the study area gains about 110 W m^{-2} (Table 1, Fig. 2) from short- and long-wave radiation.

Daily variations in net radiation fluxes are governed by changes in solar radiation; the long-wave radiation remains stable owing to the stability of the sea-surface air temperatures and the cloud cover (Fig. 3).

Although the sensible and latent heat fluxes appear small, they are nevertheless significantly higher than the climatic average heat fluxes for the Norwegian and Barents Seas: 2.8 W m^{-2} in June and 2.3 W m^{-2} in July (Orvig 1970).

The distributions of the sensible, latent and total heat fluxes (Fig. 4) correlate quite well with the courses of the main streams of the Atlantic Waters. They are higher along the continental slope, and near ridges and fracture zones.

If we combine the short- and long-wave radiation with the sensible and latent heat fluxes we find that in summer in the WSC area the sea surface gains c. 70 W m^{-2}. These values are not far from the figures given by Häkkinen & Cavalieri (1989).

This means that all the heat lost by Atlantic Water plus the heat gained by the sea surface from short-wave radiation flows to the surrounding waters of the Barents, Norwegian and Greenland Seas.

Both barotropic and baroclinic forcing are important in WSC dynamics; so is the bottom topography (Fahrbach et al. 2001, Piechura et al. 2001). Carried by the West Spitsbergen Current, Atlantic Water flows to the north in a complicated pattern: sometimes it is transported in one stream, sometimes in 2 or more (Figs. 5, 6). However, the most intensive stream is usually found over the continental slope, with a second and sometimes a third one (both of the latter are weaker than the main stream) farther to the west and over the eastern slope of the Mohn and Knipovich Ridges. In any case, the volume, mean salinity and temperature of Atlantic Water generally decrease northwards.

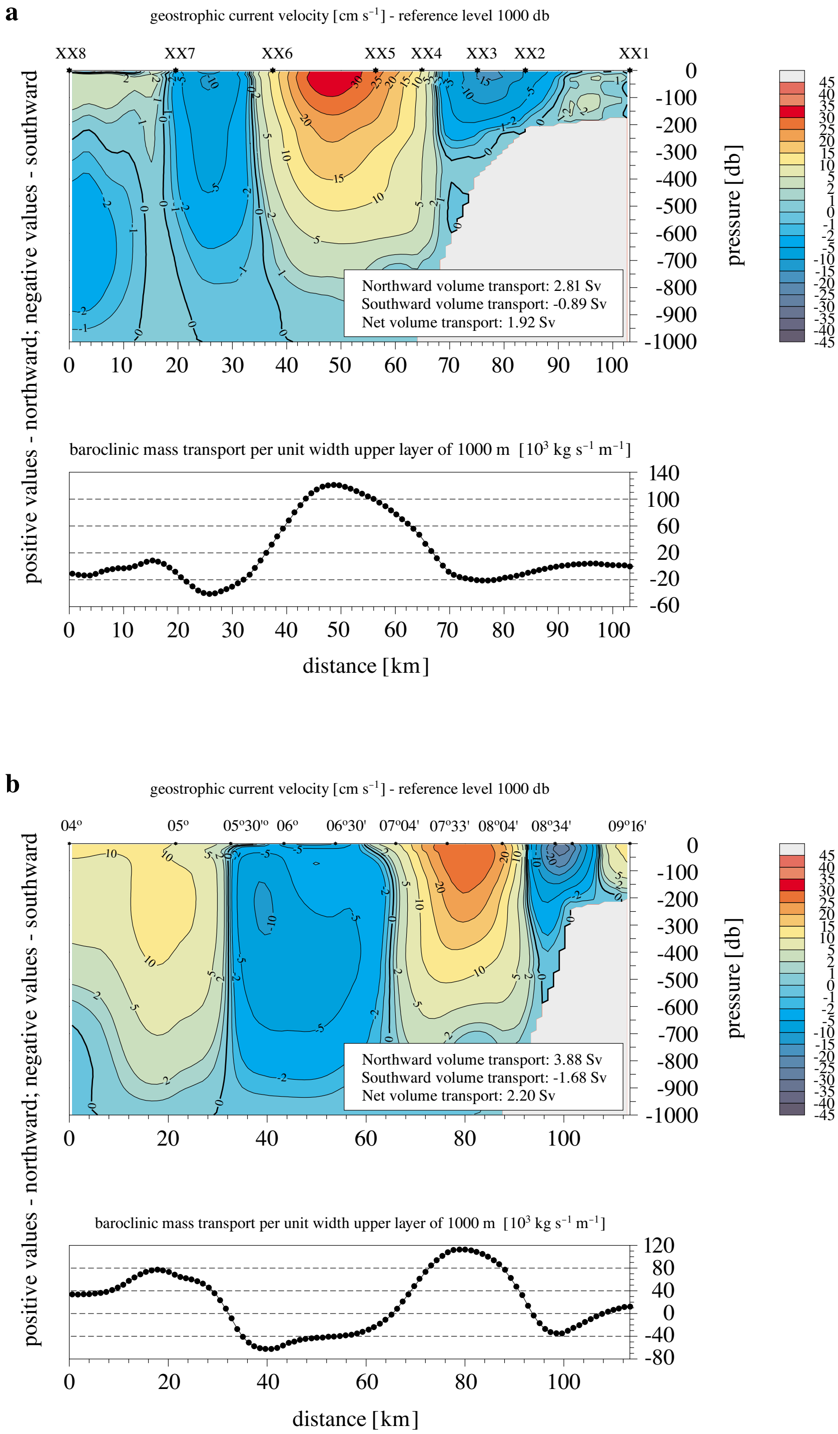

Fig. 5. Transect 'XX'

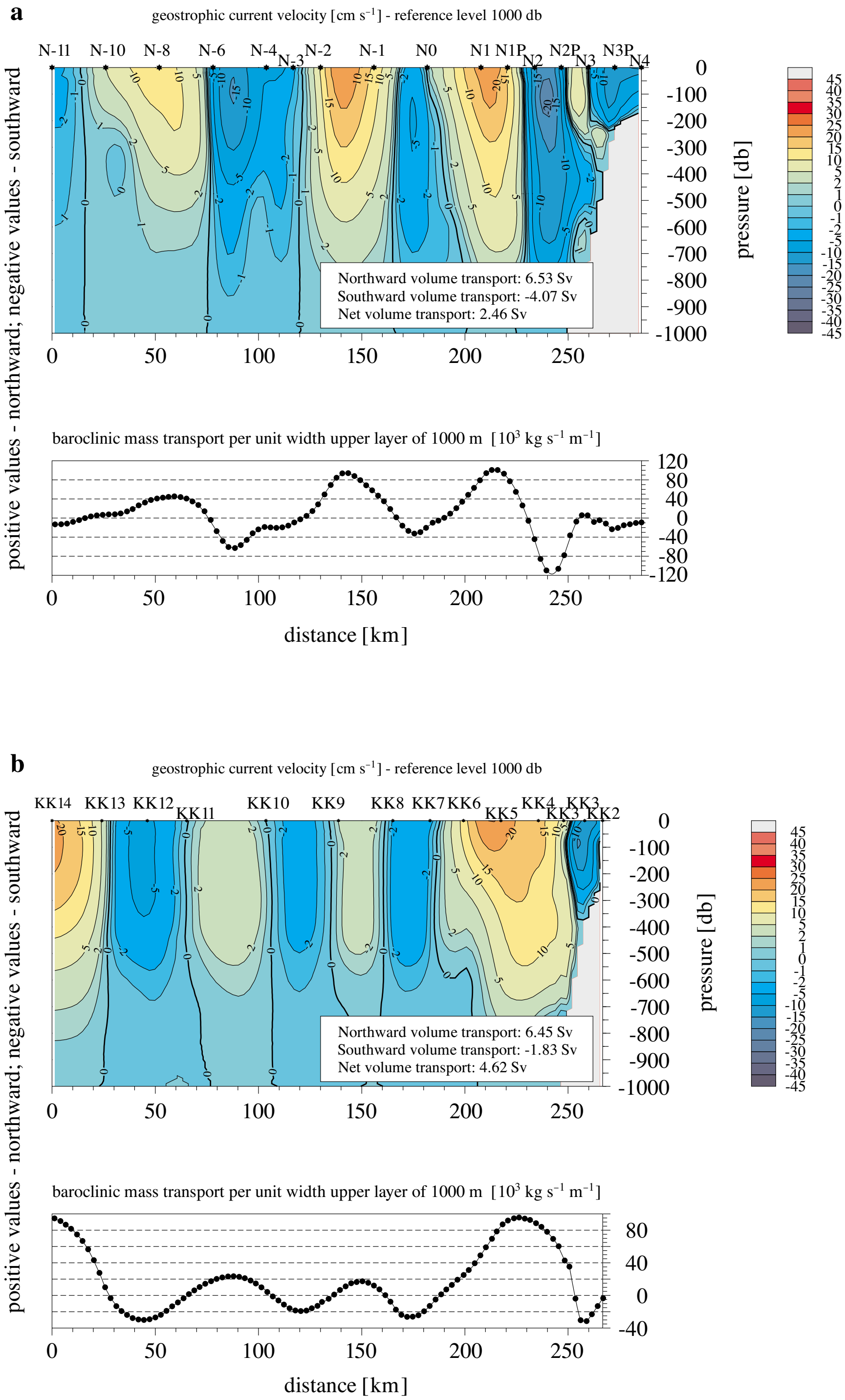

Fig. 6. Transect 'N'

An increase in heat and salt transport in the northernmost part of the study area (Table 2) following the decrease in the middle part was observed, whereas a steady decrease in volume, heat and salt transport in a northerly direction should be expected. There could be more than one reason for this. First of all, we used transects of varying length. It is possible that the northernmost transects did not cover all of AW, only the most intensive flow above the continental slope. Secondly, the WSC is a complicated multi-path current, so failure to cover all parts of WSC could have led to the volume transport being over- or underestimated. Thirdly, the inflow of AW to the Nordic Seas is very variable on a time scale of days (Orvik et al. 2001). As a result of these variations on the one hand, and because we did not perform our measurements at one single instant on the other, it would appear from the results that mass is not being conserved. Additionally, we have to take into account the errors in our measuring techniques and calculations – these are quite high, as can be seen in Table 2. Nevertheless, this is a very interesting question and requires further investigations.

The horizontal fluxes of heat carried by AW varied from about 3×10^5 W to 14×10^5 W, depending on the quantity of AW, its temperature and the velocity of the current. The highest fluxes were measured along the northern transects, where AW flow was compressed more towards the stream over the continental slope.

Assuming that about 1/3 of the volume, heat and salt carried by AW along transect AA (70–72°N) enters the Barents Sea, a rough estimate of the heat lost by AW on its c. 1000 km journey to the surrounding waters of the Norwegian and Greenland Seas and the local shelf waters off West Spitsbergen is about 60–70 TW. This yields average heat fluxes of approximately 540 W m^{-2}. The heat fluxes in the north are much higher – about 1600 W m^{-2} – than in the south, where they are c. 350 W m^{-2}.

5. Conclusion

According to data collected during summer 2000 by r/v 'Oceania' in the West Spitsbergen Current area, the sea surface gains about 110 W m^{-2} of radiation energy (the sum of short- and long-wave radiation).

Calculation of sensible and latent heat fluxes shows that the sea surface loses about 40 W m^{-2} to the atmosphere.

Altogether, during June and July the sea surface receives about 70 W m^{-2} of energy. Besides the Barents Sea and the Arctic Ocean, the surrounding waters of the Norwegian and Greenland Seas and shelf waters are large sinks for the heat and salt carried by AW during summer: they receive about 60–70 TW of heat and 900×10^3 kg $\times$ s^{-1}.

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