Seasonal variations in the Atlantic water inflow to the Nordic Seas

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ABSTRACT

The inflow of warm and saline Atlantic water to the Nordic Seas occurs through three separate branches. The westernmost of these, the North Icelandic Irminger Current, has been monitored since 1985 with moored Anderaa current meters and regular CTD cruises. The other two branches that flow through the Iceland-Faroe and the Faroe-Shetland gaps respectively have been monitored by moored ADCP's and CTD sections since 1994 within the Nordic WOCE and VEINS programmes. Although there are gaps in the observations, they allow a consistent picture of the total inflow to be constructed and they allow an estimate of the seasonal variation of fluxes. We find that the two westernmost branches have seasonal variations of similar magnitudes; but almost opposite phase, so that the combined flux of Atlantic water between Greenland and the Faroes does not have a clear seasonal variation. The third branch, through the Faroe-Shetland Channel, also demonstrates a balance, but here it is between outflow of Atlantic water from the Nordic seas close to the Faroes, and inflow on the Scottish side. The combined net flux of Atlantic water through the Faroe-Shetland Channel has little seasonal variation. For the total Atlantic inflow to the Nordic Seas we have not been able to establish a consistent seasonal cycle and conclude that, if there is such a cycle, it can not exceed 1 Sv in amplitude as compared to the 8 Sv determined for the average flux. This has implications for the possible driving mechanisms that can be considered for the Atlantic inflow.

INTRODUCTION

The inflow of warm and relatively saline water from the Atlantic across the Greenland-Scotland Ridge into the Nordic Seas and from there to the Barents Sea and the Arctic is a dominant factor in the oceanography of the Arctic Mediterranean (Nordic Seas and Arctic Ocean). The magnitude and phase of a possible seasonal variation of this inflow is therefore a necessary component of a description of this area, but may also give hints as to the driving forces responsible for the inflow.

The inflow is divided into three distinct branches that flow through the Greenland-Iceland Gap (the "GI-inflow"), the Iceland-Faroe Gap (the "IF-inflow"), and the Faroe-Shetland Channel (the "FS-inflow") respectively (Fig. 1). Recently, values for the fluxes of each of these branches have been estimated based on direct current measurements combined with hydrography (Kristmannsson, 1998; Hansen *et al.*, 1999a). The Greenland-Iceland branch is clearly the weakest one while the other two branches carry similar fluxes of Atlantic water (Fig. 1).

Investigations on seasonal variation of Atlantic inflow were reported already early in the 20th century (Jacobsen, 1943; Tait, 1957; Stefánsson, 1962) and have been frequent since then. Most of these studies have focused on parts of the inflow, only, especially on the FSC-inflow, and a large part has relied on methods that are based on unproven, and in many cases wrong, assumptions of reference level velocities (Hansen and Østerhus, 2000).
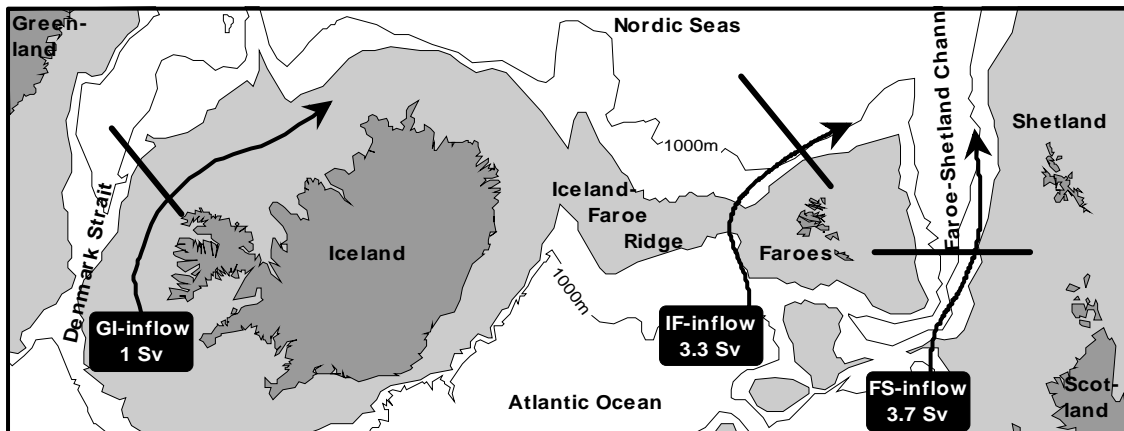

Figure 1. The inflow of Atlantic water to the Arctic Mediterranean occurs through three separate gaps over the Greenland - Scotland Ridge. Black boxes indicate flux estimates of Atlantic water for each of the three inflow branches based on Kristmannsson (1998), Hansen *et al.* (1999b), and Turrell *et al.* (1999). Thick lines indicate main sections from which observations discussed in this paper have been obtained. The shaded area is shallower than 500 m.

Here, we combine direct measurements of inflow fluxes for all three branches in an attempt to obtain an overall estimate of the seasonal variation of the total inflow. The basic dataset includes hydrographic and current measurements from long-term national monitoring programs and current measurements with traditional current meters as well as moored ADCP's within the Nordic WOCE and VEINS projects.

Since the observational methods and processing have been different in the different areas, we discuss each of the three inflow branches separately in the following three sections while the synthesis and its implications are left for the discussion section.

THE GREENLAND - ICELAND GAP

Material and methods

The Atlantic inflow to the north icelandic shelf has been monitored with a single mooring with Aanderaa current meters at two depths. From 1985 to 1993 the mooring was situated on the Kögur section. It was then moved to the Hornbanki section a little further to the east in 1993 (Fig. 2). CTD data are available from the sections at least four times per year, in February, May/June, August and November.
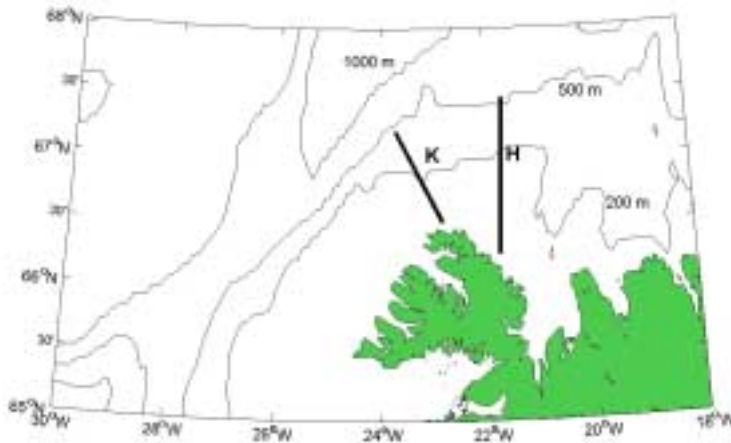
Figure 2. The two lines indicate the Kögur and the Hornbanki sections and the letters K and H indicate the positons of the moorings.

Results

The current meter data from the Kögur section from 1985-1990 were studied by Kristmannsson (1998) and we will use his data, together with data from 1991-1992. In Figure 3, the eastward velocity is shown for each month available (+) and the average is given as dots connected by a line. It is evident that the average indicates that the flow is weaker during late winter January-April than at other times. However the data are very much spread and the seasonal signal is not at all clear when looking at individual years. There can be very large differences between consecutive months so the short term variability is large.
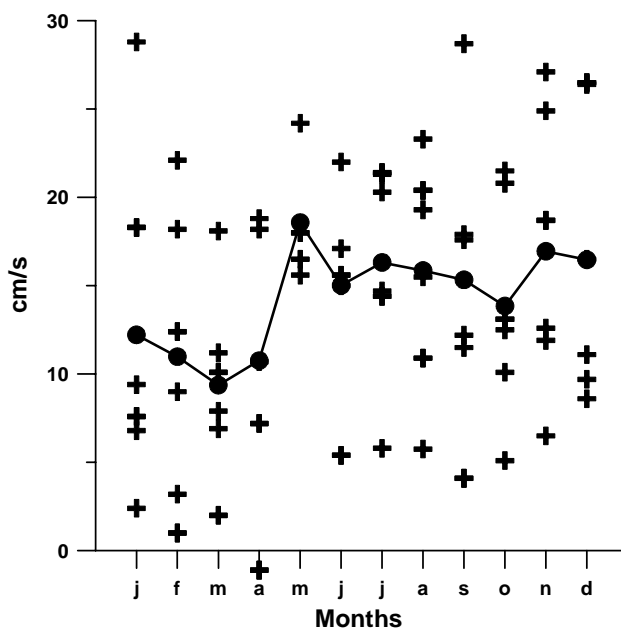
Figure 3. The mean eastward velocity at the upper current meter (100-139 m depth) is shown for each month available (+). The average is given as dots connected by a line.
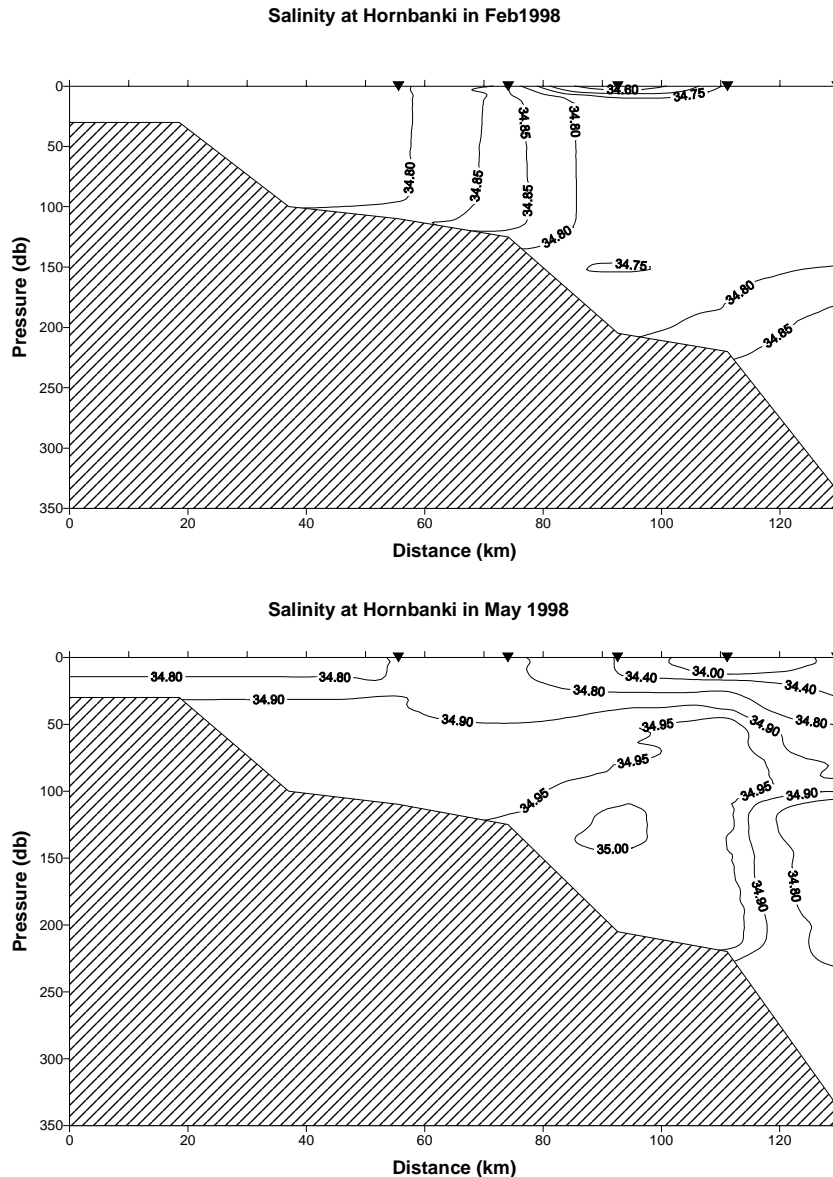
Salinity at Hornbanki in Feb1998

Salinity at Hornbanki in May 1998

Figure 4. The salinity distribution at the Hornbanki section in February/March and May 1998.

This also holds true for the water mass properties as can be seen in Figure 4 of the salinity distribution at the Hornbanki section from February and May 1998. In May there is a clear presence of Atlantic water with a core above 35 at about 100 m depth, while in February no undiluted Atlantic water was present in the section and the maximum salinity was below 34.87. Thus, besides variability in the speed, there are also great variations in the water mass properties even within a few months and probably also on shorter timescales.

The transport of the inflow has been estimated using these data by Kristmannsson *et. al.*, (1989) and they found that the mean transport of water with temperatures above 4°C was about 1 Sv during the first year of the measurements. The average of the monthly transports of the flow of water with temperatures above 4°C for the five year period 1985-1990 was estimated as 1.5 Sv (Kristmannsson, 1998). The transport was found to vary during the measuring period from 0 Sv in February/March 1990 to 2.8 Sv in January 1987. If the transport is assumed to be proportional to the velocity of the upper current meter shown in Figure 3, a minimum transport of 1 Sv is observed in March and there is a maximum of 2 Sv in May, so if there is a consistent seasonal variation in the inflow of AW through the Denmark Strait then it is probably less than 40% of the mean flow.

THE ICELAND - FAROE GAP

Material and methods

Between Iceland and the Faroe Islands, our observations are from a section extending from the Faroe Plateau northwards along the 6° 05'W meridian (Fig. 5). In the southern part of this section, the Atlantic water forms a wedge of warm and salty water separated from the relatively colder and fresher waters farther north by a front that hits the Faroe Plateau at typical depths of 400 - 500 m and reaches the surface in the Iceland-Faroe Front (Fig. 6).

The observations along this section are from repeated CTD surveys at fixed standard stations and from repeated deployments of moored ADCP's at fixed locations (Figs. 5 and 6). The regular CTD observations on this section were initiated in 1987 and have been made during all seasons of the year, although more frequently in summer.

Data from a total of 35 cruises with complete coverage out to standard station N10 (Fig. 5) are

Figure 5. The CTD standard section N is shown as a line with the standard stations indicated by black rectangles, labeled N01 to N14 northwards. Main ADCP mooring sites are indicated by circles. Dotted curve indicates the general location of the Iceland-Faroes Front. Shaded areas are shallower than 500 m.

used in this paper and Figure 6 shows the average temperature and salinity fields based on the whole data set. A more complete description of this data set was given by Hansen et al. (1999b).
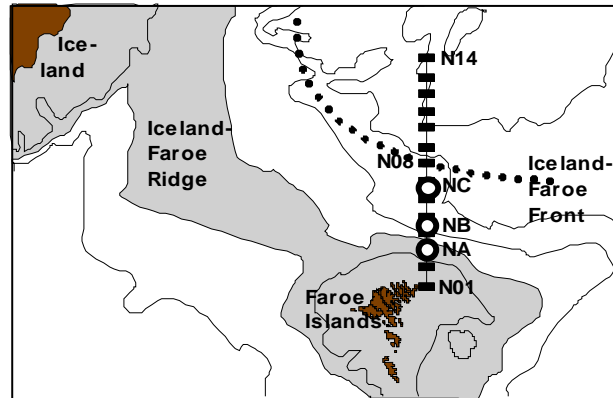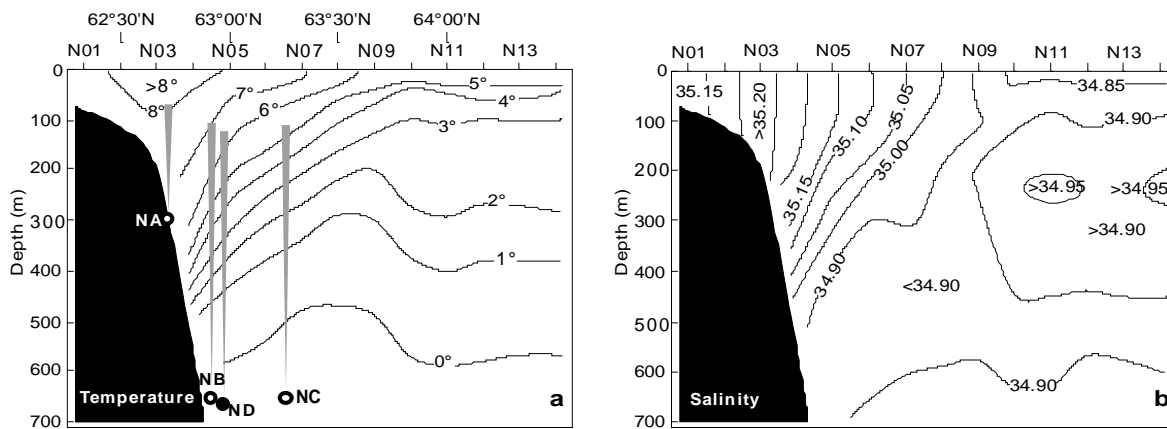

Figure 6. Average distributions of temperature (a) and salinity (b) based on CTD observations by R/V Magnus Heinason in the period 1987 - 1999 (35 cruises for stations N01 to N10, reducing to 24 cruises for station N14). ADCP mooring sites are shown by circles with sound beams shown by shading (with exaggerated width).

The 1999 paper by Hansen et al. also gives details of the acquisition and preprocessing of the ADCP data although here we include data from a further deployment with one more year of successful acquisition at sites NA, NB, and NC. The total extent of ADCP coverage north of the Faroes is illustrated in Figure 7.
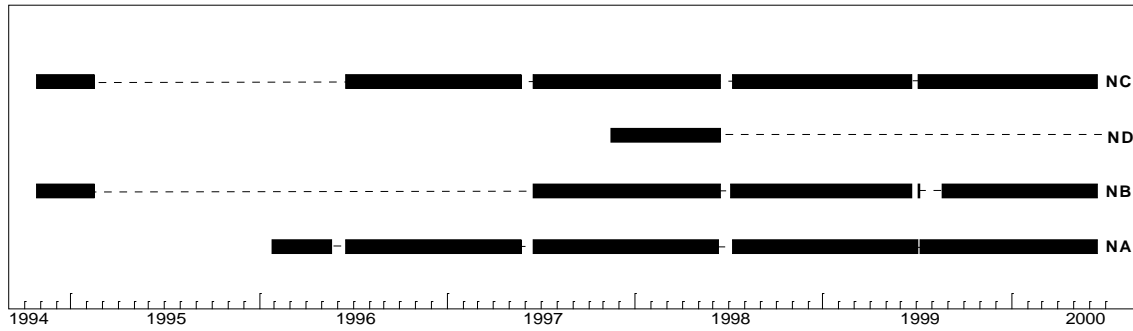
Figure 7. Overview of ADCP data (thick horizontal bars) along standard section N from October 1994 to July 1999. In addition to the three main mooring sites, one deployment was made at an additional site ND between NB and NC (Fig. 6a).

Results

The seasonal variation of the eastward velocity of the upper layer is summarized in Figure 8. This figure is based on all the ADCP measurements at sites NA, NB, and NC, 1994-2000. For sites NA and NC, there is an indication that velocities may be larger towards the east during summer than during winter; but this does not appear very significant. For the middle site, NB, there is a much clearer indication of seasonal variation with minimum eastward flow in August. Unfortunately, there are only two complete months with observations at NB in August which reduces the statistical significance.

To overcome this, we have grouped the months into four seasons in Table 1. This increases the number of observations considerably, and it appears that there is indeed a seasonal variation of eastward velocity in the uppermost 300 m at NB with lowest speed in the August - October period while the other three seasons do not seem to differ from one another significantly.

To use the ADCP measurements for volume flux estimate requires horizontal interpolation between the three measuring sites and a bit of extrapolation as well. The ambiguity in this procedure may be reduced by using the geostrophic velocity profiles deduced from the average temperature and salinity fields as described by Hansen et al. (1999b). By these methods, monthly mean volume fluxes were calculated from the ADCP measurements in the period June 1997 to June 2000.
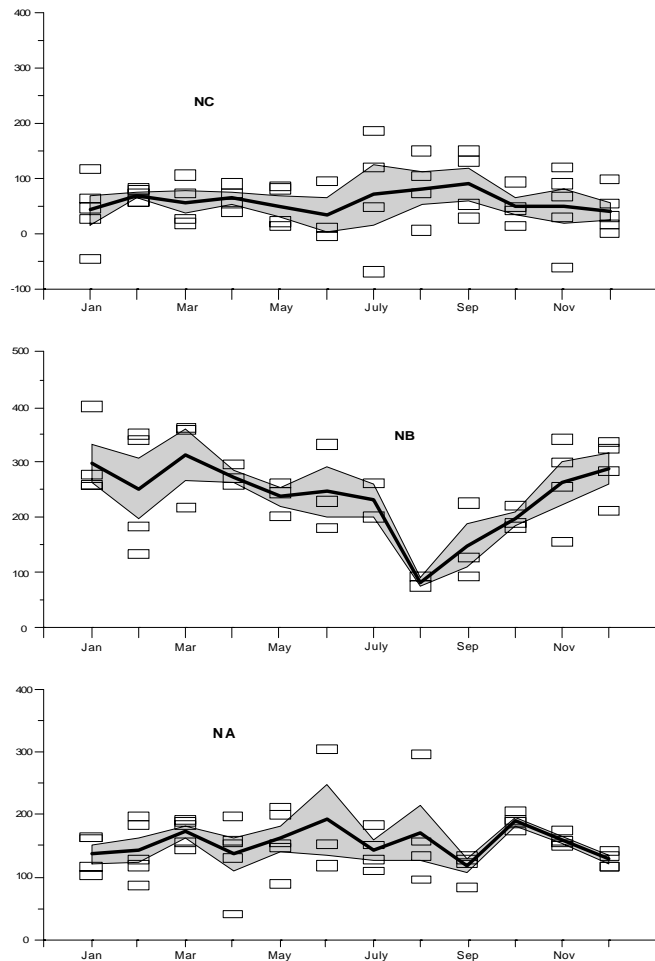

Figure 8. Monthly averaged eastward velocities (mm/s) for the 0 - 300 m depth layer at the three main ADCP mooring sites north of the Faroes. Only months with at least 15 days of observation are included. Rectangles show averages for single months. Thick line is overall average for each month. Gray area is overall average plus and minus standard error.

Table 1. Seasonal variation of eastward velocities (mm/s) for the 0-300 m depth layer at sites NA, NB, and NC (Fig. 5). Each entry represents the average ± standard error of all months in the season with number of months in brackets. Only months with at least 15 days of observation are included.

Site	Feb.- April	May - July	Aug.- Oct.	Nov.- Jan.
NA	150 ± 12 (15)	163 ± 16 (12)	159 ± 17 (12)	141 ± 7 (12)
NB	277 ± 25 (10)	239 ± 17 (8)	151 ± 21 (8)	284 ± 19 (12)
NC	64 ± 7 (13)	55 ± 21 (11)	76 ± 14 (12)	45 ± 14 (15)

The result (Fig. 9) clearly indicates a significant seasonal variation with the total volume flux in July being less than half of that in March. Figure 9 includes, however, not only Atlantic water, but also water from the East Icelandic Current and water that circulates in the Norwegian Basin (Hansen and Østerhus, 2000). This can be corrected by using the CTD observations to compute the content of Atlantic water as a function of depth and latitude and multiply that with the velocity field as detailed by Hansen et al. (1999b). Here we assume undiluted Atlantic water to be warmer than 7ºC and more saline than 35.15 while the other two water masses involved are Modified East Icelandic Water (T = 1ºC, S = 34.70) and Norwegian Sea Arctic Intermediate Water (T < 0.5ºC, S = 34.9) (Hansen and Østerhus, 2000).
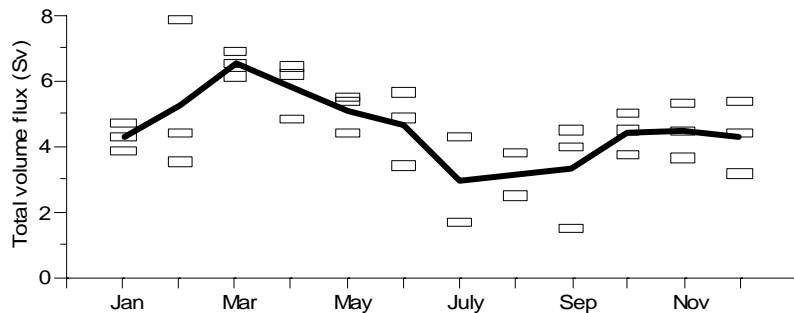

Figure 9. Monthly averaged total volume flux through the standard section N, north of the Faroes (Fig. 5) from latitude 62º 25'N to latitude 63º 35'N and from the surface down to 700 m depth. Rectangles show averages for single months. Thick line is overall average for each month.

The resulting seasonal variation of Atlantic water flux north of the Faroes (Fig. 10) is less pronounced, even if we assume that the distribution of Atlantic water content on the section does not vary seasonally (thin line in Figure 10). With this assumption, the amplitude of the seasonal flux variation (half the difference between maximum and minimum) is on the order of one Sv.
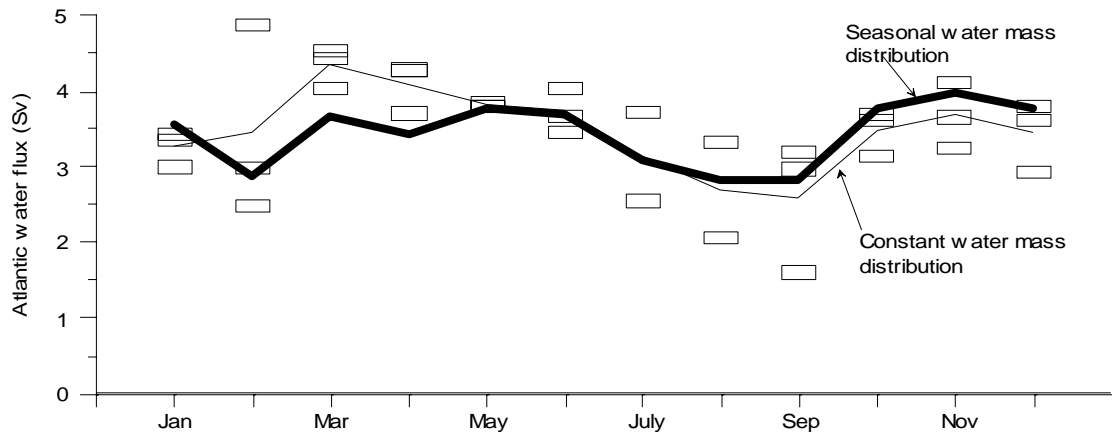

Figure 10. Monthly averaged volume flux of Atlantic water through the standard section N, north of the Faroes (Fig. 5) from latitude 62º 25'N to latitude 63º 35'N and from the surface down to 700 m depth. Rectangles show averages for single months. Thin line is overall average for each month with a constant water mass distribution on the section. Thick line is overall average for each month with the water mass distribution determined for each of the four seasons in Table 1 separately using the CTD observations.

The CTD observations indicate, however, that there is a seasonal variation of the Atlantic water distribution on the section, but this variation is opposite in phase to the velocity field. Thus, Figure 11 indicates that the relatively saline Atlantic water (gray region on the figure) is more widely distributed on the section in summer than in winter. When this is taken into account (thick line on Figure 10), the amplitude of the seasonal variation is further reduced. The variation in this case has become more irregular and the picture of a clear seasonality has disappeared which may partly be due to the small number of CTD cruises in some seasons.
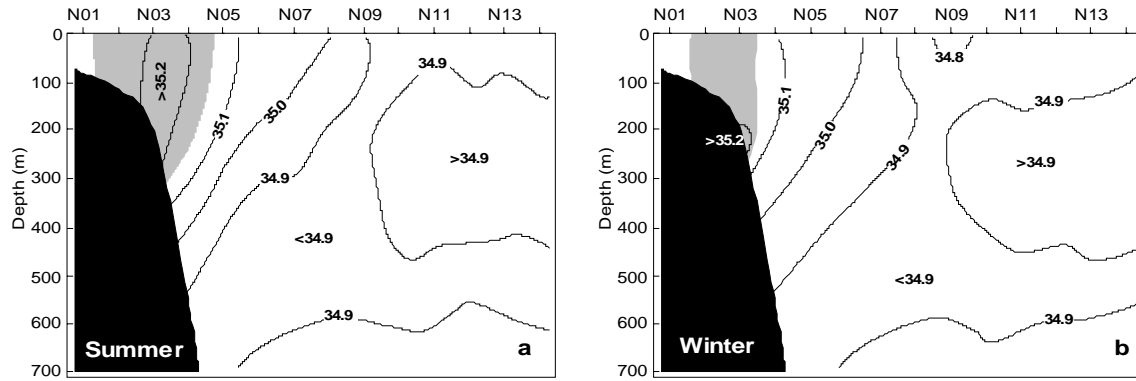

Figure 11. Average salinity distribution on the standard section north of Faroes in summer (May - Oct) and winter (Nov - April). The gray region indicates water with salinity above 35.15 - that is undiluted Atlantic water by our definition.

There are a number of assumptions and approximations involved in the calculations leading to Figure 10 (Hansen et al., 1999b) so the result should not be overinterpreted. If there is a consistent seasonal variation in the inflow of Atlantic water between Iceland and the Faroes, then it is probably relatively small, with an amplitude on the order of 0.5 - 1 Sv and with a minimum in July - August.

THE FAROE-SHETLAND CHANNEL

Material and Methods

The Atlantic inflow through the Faroe-Shetland Channel is monitored along a section running southeastwards from the southern tip of Faroe towards the Scottish continental shelf (Fig. 12). This southern (S) standard section is monitored by five ADCP moorings (SA to SE), repeatedly redeployed since October 1994, and by 12 fixed hydrographic stations which have been occupied regularly since the start of the century. The present study employs data for the period October 1994 to September 1999, and during this time there were a total of 35 CTD surveys along the standard section. Figure 13 shows the availability of valid ADCP data at the five S mooring positions during the period.

The CTD data were used to quantify the distribution of surface and intermediate waters in the Channel using a three point mixing model. From an examination of the TS characteristics during the period, Atlantic water was defined by T≥7°C and S≥35.15, and two intermediate water
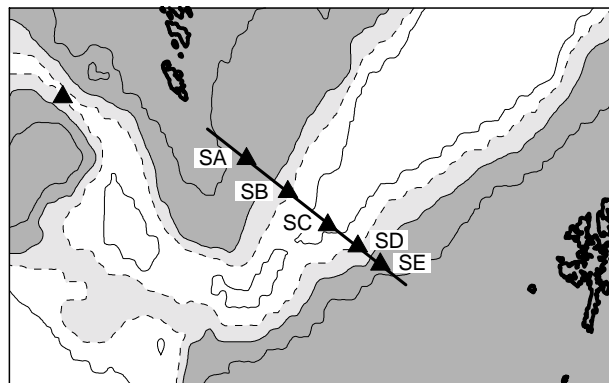

Figure 12. The Faroe-Shetland Channel, with the CTD standard section S shown as a line and the ADCP mooring sites SA to SE indicated by triangles. Shaded areas are shallower than 750 m (light shading) and 500m (dark shading). The 1000m contour is also shown.

masses, assumed to mix with the overlying Atlantic water, were determined to be Modified East Icelandic Water (T= 1.0°C, S=34.7) and Norwegian Sea Arctic Intermediate Water (T=0.5°C, S=34.9). Details of the mixture calculations are given in Turrell *et al.* (1999).

The ADCP data were de-spiked, averaged into 25m depth bins, low-pass filtered and resolved along 038°N to give along-channel speeds. Daily averages were then calculated, and employed in the estimates of transport using the method described in Turrell *et al.* (1999).
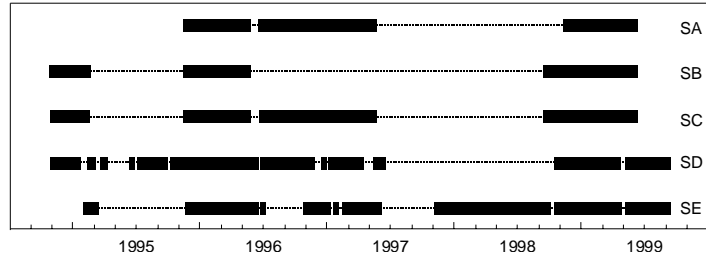

Figure 13. Overview of availability of ADCP data (thick horizontal bars) along standard section S from October 1994 to September 1999.
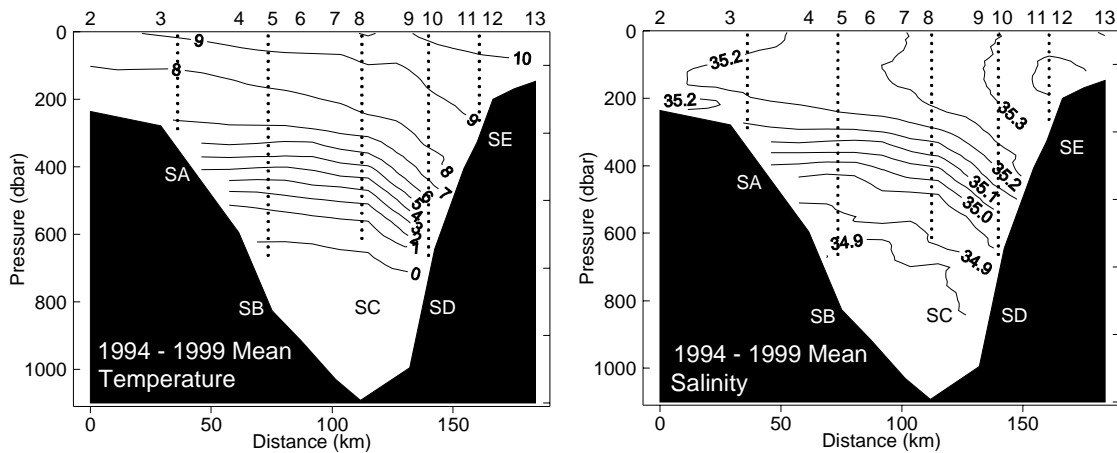

Figure 14. Average distributions of temperature (°C) and salinity along standard section S based on CTD observations by R/V Magnus Heinason and R/V Scotia during the period 1994 - 1999 (35 cruises). The section is viewed looking northeastwards, with Faroes to the left and Scotland to the right. Also indicated are the locations of valid ADCP data bins at the mooring sites SA to SE, shown by vertical lines of dots. The locations of 12 standard CTD stations are indicated along the upper axis.

Results

Figure 14 shows the average temperature and salinity fields calculated from the 35 CTD surveys during the 1994 - 1999 period, and Figure 15 shows the percentage water mass distributions estimated from these, along with the average along-channel speeds calculated from the ADCP data. These two figures show that mooring SA monitors the Atlantic water lying on the Faroese side of the Channel. The upper 275m at mooring SB are predominantly Atlantic water, while at 425m there is a core of Modified East Icelandic Water, contributing at most 30% to the composition of the mixed water. Below this core there is an increasing contribution of Norwegian Sea Arctic Intermediate Water. The thickness of the Atlantic layer increases towards the Scottish slope, with its base lying at 300m at the central mooring SC, and at 425m at mooring SD. Mooring SE lies wholly within the core of highest salinity water adjacent to the Scottish slope.

The average along channel speeds (Figure 15 d) indicate flow into the Nordic Seas in the upper Atlantic water at moorings SE, SD and SC. The bottom of the inflow lies at 550m at SD, and at 500m at SC. Therefore the inflow between 300-500m and 425-550m, at SC and SD respectively, consists of mixed Atlantic / intermediate water. Outflow exists beneath the inflow at SC and SD, and throughout the remainder of the Channel, with a maximum in the Atlantic water at SB.
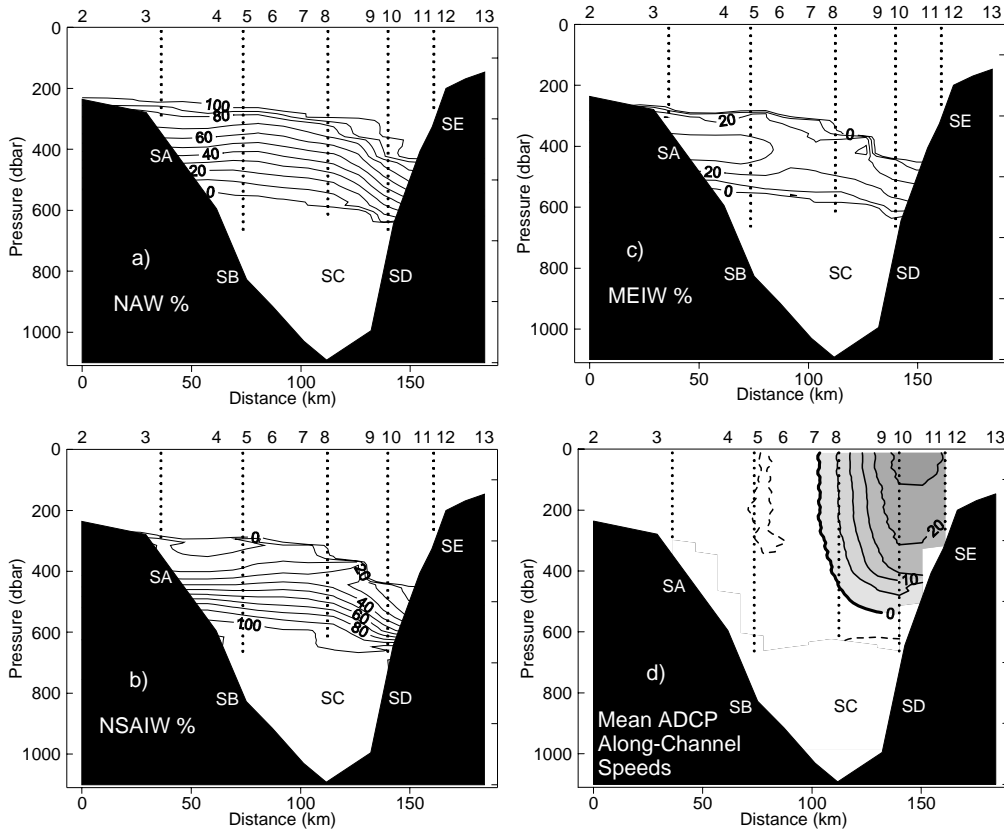
Figure 15. Percentage distributions of three water masses, a) NAW – Atlantic Water, b) MEIW – Modified East Icelandic Water, c) NSAIW – Norwegian Sea Arctic Intermediate Water, calculated using the average distributions of temperature and salinity seen in Figure 14. d) Overall mean distribution of along-channel (towards 038°N) speeds (cm s^{-1}) calculated using the ADCP observations along standard section S during the period October 1994 – September 1999. Shaded areas are speeds directed towards the northeast, into the Norwegian Sea. ADCP mooring sites (SA to SE) are shown by small circles indicating the location of valid data bins. The location of 12 standard CTD stations are indicated along the upper axis.

The average along-channel speeds in the 0-200m layer (Fig. 16) indicate a degree of seasonality in the inflow at SE, where current speeds are greatest in August, September and October. At SD summer and winter speeds are similar, although there are minima in inflow in spring (May) and autumn (November). At the central mooring SC there is no clear seasonality, while at SB and SA there is some indication that outflow is at a maximum in the summer months, although these are poorly sampled at SB.

To examine this further, the along-channel speeds have been averaged over seasons (spring - May, June, July; summer - August, September, October; autumn - November, December, January; winter - February, March, April). Their distributions across the section are shown in Figure 17, and the average speeds in the 0-200m layer are given in Table 2. It should be noted from Table 2 that there are generally less months with more than 15 days of valid data at the S mooring locations compared to the N moorings (Table 1), and so the significance of the seasonal means is reduced, particularly in the core of the outflow at SB.

In spring the inflow is at its widest (Fig.17), extending out to SB in the upper 100m. In summer the current intensifies, deepens and narrows, but the outflow also increases to a maximum (although this may be due to the single time the month of October was sampled at SB being a high outflow event - Fig 16). In autumn the inflow becomes shallower, while in the winter it again deepens, and outflow increases.
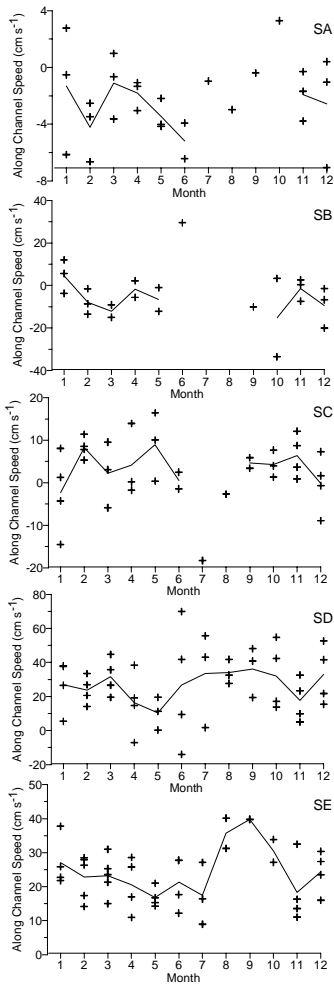
Table 2. Seasonal variation of along-channel speeds (cm s⁻¹) for the 0-200 m depth layer at sites SA to SE (Fig. 12). Each entry represents the average ± standard error of all months in the season with number of months in brackets. Only months with at least 15 days of observation are included.

Site	Feb.- April	May - July	Aug.- Oct.	Nov.- Jan.
SA	-2.4 ± 0.7 (9)	-3.6 ± 0.7 (6)	0.0 ± 1.5 (3)	-1.9 ± 1.2 (6)
SB	-7.3 ± 2.2 (7)	5.4 ± 10.2 (3)	-13.5 ± 8.8 (3)	-2.1 ± 5.0 (3)
SC	5.2 ± 1.9 (10)	1.6 ± 4.4 (6)	3.3 ± 1.4 (6)	0.8 ± 2.9 (6)
SD	23.9 ± 3.8 (12)	23.9 ± 8.2 (10)	33.9 ± 4.2 (10)	25.3 ± 4.4 (10)
SE	22.3 ± 1.6 (14)	18.7 ± 1.9 (11)	35.3 ± 2.0 (6)	24.4 ± 2.1 (11)

Figure 16. Monthly averaged along-channel speeds (cm s⁻¹) for the 0 - 200 m depth layer at the five ADCP mooring sites south of the Faroes. Only months with at least 15 days of observation are included. Crosses show averages for single months. The line is the overall average for each month, where there are more than 1 sampled month. Positive speeds are directed towards the northeast, into the Norwegian Sea.

Figure 17. Seasonal means (Spring - May, June, July; Summer - August, September, October; Autumn - November, December, January; Winter - February, March, April) of along-channel (towards 038°) speeds (cm s⁻¹) calculated using the ADCP observations along standard section S during the period October 1994 – September 1999. Shaded areas are speeds directed towards the northeast, into the Norwegian Sea.
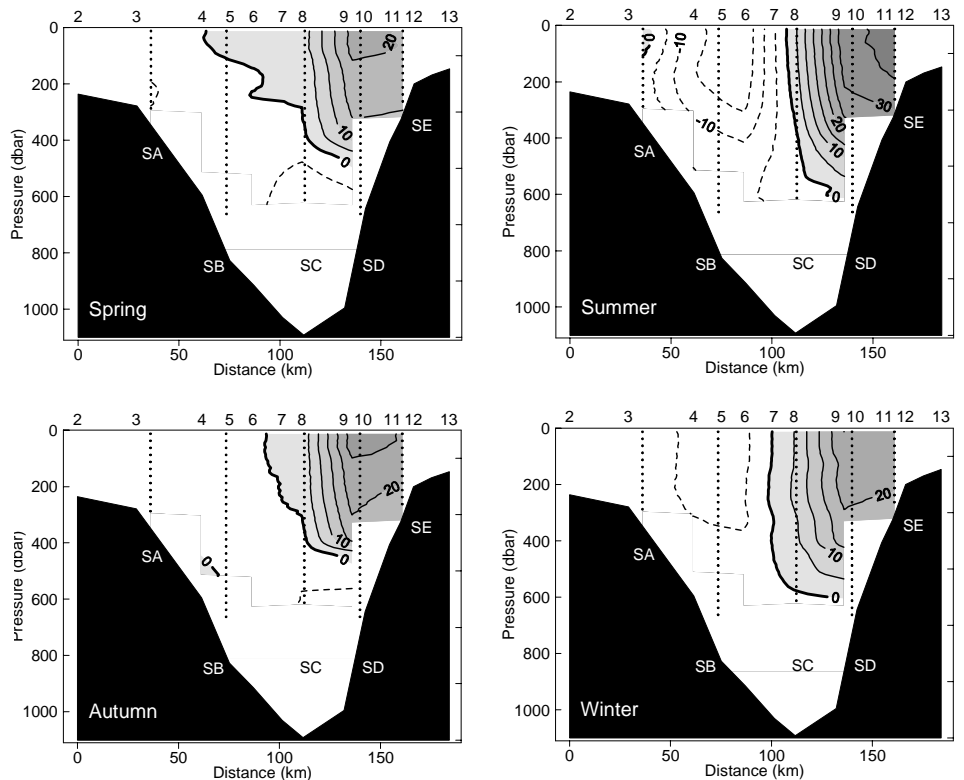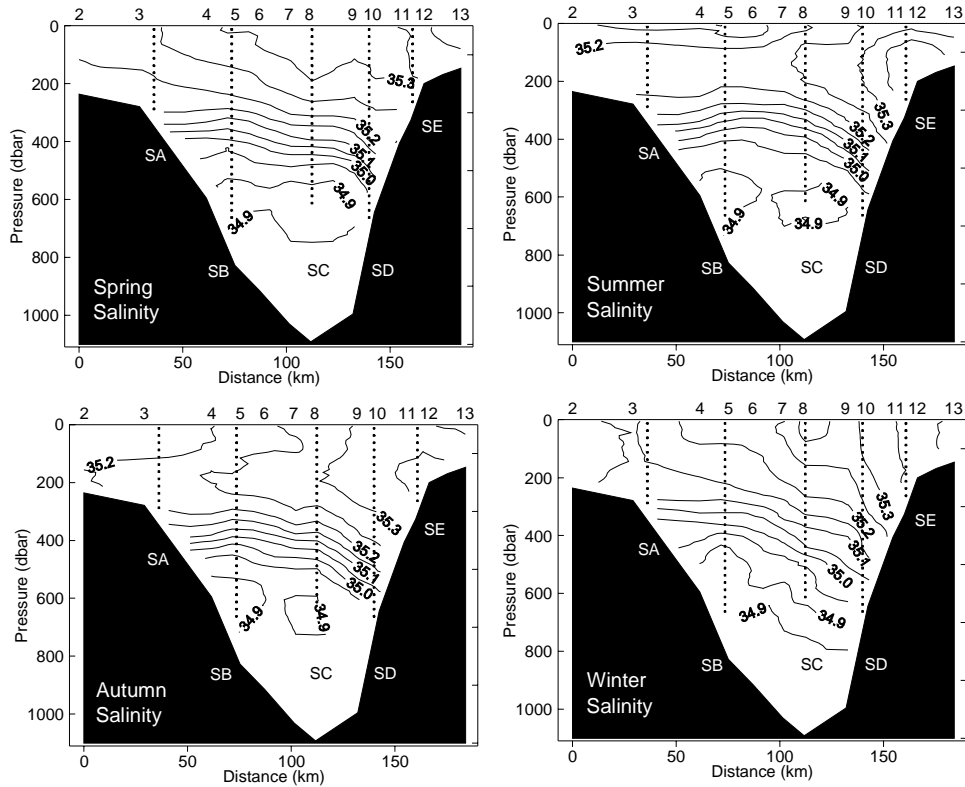
Figure 18. Seasonal means of salinity on the S standard section.

The seasonal distributions of average along-channel speed were combined with seasonally averaged distributions of water mass distributions (derived from average temperature and salinity fields – Fig.18) in order to compute seasonal fluxes using the method described in Turrell *et al.* (1999). Table 3 presents the seasonal fluxes for the three water masses used in the mixing model, along with the flux calculated using the overall 1994-1999 average fields. The net inflow of Atlantic water differs very little between seasons, with less than 0.1Sv variation between summer, autumn and winter from the average 3.6Sv. The spring inflow of Atlantic water is weakest, at 2.6Sv. When the balance of inflow and outflow, which combines to produce the net inflow, is examined, strong Atlantic water inflow during summer and winter is balanced by strong outflow. There is little seasonality in the net transport of Modified East Icelandic Water, although the transport of Norwegian Sea Arctic Intermediate Water is greater in summer and spring (~1Sv) compared to autumn and winter (~0.3Sv). It must be remembered that the ADCP array was designed to sample the Atlantic water inflow, and does not capture the outflow below 700m. During this observational programme the outflow has been separately monitored in the Faroe Bank Channel (Østerhus *et al.*, 1999).

Table 3. Overall (94-99) and seasonal average fluxes for each of the three water masses used in the three-point mixing model and applied to the seasonal mean along-channel speed fields to calculate fluxes. Postive values indicate flow towards the northeast, into the Norwegian Sea.

	Outflow (Sv)			Inflow (Sv)			Net (Sv)		
	NSAIW	MEIW	AW	NSAIW	MEIW	AW	NSAIW	MEIW	AW
94-99	-0.6	-0.1	-1.1	0.1	-0.1	4.7	-0.5	-0.1	3.6
Spring	-0.8	-0.1	-0.9	0.0	-0.1	3.5	-0.8	-0.1	2.6
Summer	-1.0	-0.3	-3.1	0.1	-0.2	6.7	-0.9	-0.2	3.6
Autumn	-0.5	-0.1	-0.8	0.0	-0.1	4.5	-0.5	-0.1	3.7
Winter	-0.3	-0.3	-1.2	0.1	-0.2	4.9	-0.2	-0.2	3.7

DISCUSSION

Having discussed each of the three gaps in Figure 1 separately, we must try to combine them into a coherent picture so that we can estimate the seasonal variation of the total Atlantic water inflow to the Nordic Seas. Unfortunately, we do not have simultaneous observations in all three gaps for a sufficient number of years to determine the seasonal variation with a high accuracy; but we can put some restraints on the probable range.

In the Greenland - Iceland Gap the data indicate that the flow is weaker during late winter January-April than at other times. The amplitude of the seasonal variations in the volume transport is probably within 0.5 Sv from the mean transport. This, however, only reflects the seasonal velocity variation. As noted (Fig. 4), the Atlantic water content can vary in the same sense which would strengthen the seasonal signal, although hardly by more than by a factor of two. Thus, the most probable amplitude for the seasonal variation of the Greenland - Iceland Atlantic inflow should be somewhere in the range of 0.5 - 1 Sv with a minimum in winter.

In the Iceland - Faroe Gap, a smoothed version of the thick line in Figure 10 would be our best estimate for the seasonal variation of the Atlantic water flux, or perhaps some intermediate between the two lines in the figure. This signal thus seems to have an amplitude of similar magnitude as that in the Greenland - Iceland Gap, but with a phase that is close to being opposite. If we combine the flows through the two gaps, this implies, that the inflow of Atlantic water between Greenland and the Faroes cannot have a large seasonal variation. The seasonal amplitude of the combined flow can hardly exceed 0.5 Sv.

The ADCP and CTD monitoring performed along the S section across the Faroe-Shetland Channel has revealed a degree of seasonality in temperature, salinity and current speed distributions. However, when these are combined to compute the net transport of Atlantic water through the section, there appears to be a balance between outflow and inflow resulting in no clear seasonal variation. Turrell *et al.* (1999) reached a similar conclusion, although the present study includes an additional two years of data (1997-1999). Some caution must still be applied, as the core of the outflow through the section has been poorly sampled, particularly for the summer months, and new data may alter the present assessment. However, until that becomes available, this study suggests that a possible seasonal variation of the resulting net Atlantic water flow through the Faroe-Shetland Channel does not exceed 0.5 Sv in amplitude.

Combining the results from the three branches in Figure 1, we thus have not been able to establish a consistent seasonal variation for the total Atlantic inflow to the Nordic Seas. If a consistent seasonal cycle exists, our results indicate that its amplitude does not exceed 1 Sv. In the total budget for the Arctic Mediterranean (Fig. 19), there is one additional inflow branch which enters through the Bering Strait and has been found to have a seasonal cycle with an amplitude of 0.5 Sv (Roach *et al.*, 1995). Combining this with our results, we conclude that a possible seasonal cycle in the total inflows to the Arctic Mediterranean does not exceed 1.5 Sv in amplitude.
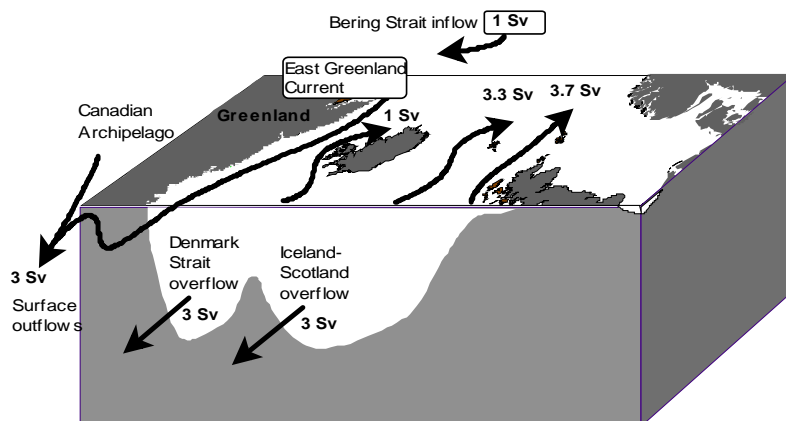

Figure 19. Water budget for the Arctic Mediterranean with fluxes of the main inflow and outflow branches in Sverdrup (Sv).

An imagined imbalance between inflows and outflows of 1 Sv over a three-month period would require an average water level change of about half a meter over the whole of the Arctic Mediterranean. We must therefore assume a fairly tight balance between inflows and outflows and conclude that a possible seasonal cycle in the total outflows must have similar bounds as the inflows. In Figure 19, two thirds of the total outflow is carried by the various overflow branches which do not seem to have any significant seasonal

cycle (Jónsson, 1999; Østerhus *et al.*, 1999). A seasonal cycle in the total inflow should mostly be balanced by a similar cycle in the surface outflows. Our results therefore also imply that the surface outflows do not vary seasonally by more than 50% of the average flux. This would seem a reasonable result. Much larger seasonal amplitudes of the total inflows would, on the other hand, have been more difficult to reconcile with Figure 19.

Various driving mechanisms have been suggested for the Atlantic inflow: Wind stress, estuarine, and thermohaline (i.e. formation of deep and intermediate waters in the Arctic Mediterranean). All of these have distinct pronounced seasonal cycles, and our conclusion might therefore seem somewhat paradoxical. Hansen and Østerhus (2000) used the budget in Figure 19 to argue that thermohaline forcing was the dominant mechanism and it, certainly, is most intensive during winter and spring. The link between the vertical and the horizontal exchanges is not direct, however. The direct action of the thermohaline forcing is to replenish the cold water at depth in the Arctic Mediterranean and hence to maintain the horizontal pressure difference between the Arctic Mediterranean and the Atlantic just above sill level of the Greenland - Scotland Ridge. In a simple conceptual model this pressure difference drives the deep overflows which then induce a sea level fall in the Arctic Mediterranean that drives the surface inflows.

Although created by seasonal atmospheric cooling, the horizontal pressure gradients are the accumulated result of many seasons. A rough calculation will verify that with today's flux values, the overflows could continue for at least a few decades even if all deep and intermediate water formation were to stop in the Arctic mediterranean before the pycnocline fell below sill level. We therefore should not expect large seasonal variations, neither in pressure gradients, nor in the fluxes that they drive. Our results therefore support the idea of thermohaline forcing as the main driving mechanism.

At first glance, our results seem somewhat in conflict with flux estimates on the Svinøy section, recently reported by Orvik *et al.* (1999). They divide their section into two parts where they have resolved the inner part well with a number of current meter moorings. For this branch, they find a seasonal cycle in most years with maximum Atlantic water flux in winter. They also find a fairly good correlation between flux and the NAO (North Atlantic Oscillation) index in most years. These results can be reconciled with our observations if we assume that the inner branch on the Svinøy section receives a variable fraction of the Atlantic water inflow through the Iceland - Faroe Gap. We find some support for this conjecture in the large variability that we observe for the recirculation in the Faroe-Shetland Channel (Tables 2 and 3) and also in Blindheim *et al.*'s (2000) observation that the width of the Norwegian Atlantic Current is negatively correlated to the NAO index although that was at longer timescales.

This explanation requires that the Atlantic water flux of the outer (western) branch on the Svinøy section varies in opposite phase to the flux of the inner branch which is in direct conflict with Orvik *et al.*'s (1999) findings. Their results for the outer branch are, however, not based on direct current measurements, but rather on hydrographical observations at a single station. We are not convinced that this method is sufficiently robust to allow calculation of the seasonal cycle of the Atlantic water flux of the outer branch.

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