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Measured volume, heat, and salt fluxes from the Atlantic to the Arctic Mediterranean

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[1] The flow of warm and saline Atlantic water towards the Arctic crosses the Greenland-Scotland Ridge in three current branches. Since the mid 1990's, extensive monitoring with quasi-permanent moorings and regular CTD cruises has been in operation on three sections crossing the branches. Averaged over the years 1999 to 2001, values of volume, heat (relative to 0°C) and salt flux due to the total Atlantic inflow across the Greenland-Scotland Ridge into the Nordic Seas are estimated as 8.5 Sv (1 Sv = 10^6 $m^3 \cdot s^{-1}$), $313 \cdot 10^{12}$ W, and $303 \cdot 10^6$ $kg \cdot s^{-1}$. In this period, the average temperature and salinity of the Atlantic inflow were 8.5°C and 35.25, respectively. Within the observational uncertainty, we do not find any significant seasonal variation of the volume flux, but a negative correlation between the inflow flux through the Faroe-Shetland Channel and through the other two gaps was indicated. **Citation:** Østerhus, S., W. R. Turrell, S. Jónsson, and B. Hansen (2005), Measured volume, heat, and salt fluxes from the Atlantic to the Arctic Mediterranean, *Geophys. Res. Lett.*, *32*, L07603, doi:10.1029/2004GL022188.

1. Introduction

[2] The flow of warm, saline water from the Atlantic Ocean (hereafter termed "*Atlantic inflow*") across the Greenland-Scotland Ridge into the Nordic Seas and the Arctic Ocean (collectively termed the Arctic Mediterranean) is of major importance, both for the regional climate and for the global thermohaline circulation. Through its heat transport, it keeps large areas north of the Ridge much warmer, than they would otherwise have been and free of ice [*Seager et al.*, 2002]. At the same time, the Atlantic inflow carries salt northwards, contributing to the maintenance of high densities in the upper layers; a precursor for thermohaline ventilation.

[3] Until recently, flux estimates for the Atlantic inflow were mainly based on budgets, assuming volume, heat, and salt conservation [*Worthington*, 1970; *McCartney and Talley*, 1984]. Here, we present results of dedicated measurements aimed at determining volume, heat, and salt fluxes for the Atlantic inflow and their variations. The observations were initiated during the "Nordic WOCE" programme and preliminary results have previously been reported [*Hansen and Østerhus*, 2000; *Østerhus et al.*, 2001; *Turrell et al.*, 2003; *Jónsson and Briem*, 2003].

[4] The Atlantic inflow is carried by three separate branches which here are termed the Iceland branch, the Faroe branch, and the Shetland branch (Figure 1). For the period from January 1999 to December 2001, we have simultaneous high-quality measurements that allow flux estimation for all of the branches and this is the data set principally discussed here. In the following sections, we first discuss our methodology in general. Then the observations and results from each of the three branches are briefly discussed. The last section combines the results and discusses typical values and variations of the fluxes of the total Atlantic inflow.

2. Methods

[5] In the literature on the Nordic Seas and Arctic Ocean, the concept of Atlantic water is often defined by its salinity, e.g. as water more saline than 35.00. Here, we define the flux of Atlantic water as the flux of water crossing the Greenland-Scotland Ridge into the Nordic Seas. Our flux measurements cover all of the Atlantic inflow but are not made on the Ridge itself and therefore the contribution from other water masses must be subtracted from the total measured volume flux in order to get the volume flux of Atlantic water.

[6] Except possibly for a surface layer, the Atlantic water is warmer than the other water masses on the sections and it is always more saline. This is illustrated by Figures 2, 3, and 4, each of which shows the salinity distribution on one of the measurement sections from a cruise in summer 2000. Figures 2–4 also show mooring arrays during periods with best coverage, and it is seen that they cover the inflow fairly well. From the current measurements, combined with geostrophy and other information, total fluxes of volume, heat, and salt through the sections can be computed on various time-scales.

[7] The method used for eliminating the contributions from other sources is based on determining the Atlantic water fraction on each section as a function of time. For the two easternmost branches, the sections are divided into sub-areas and the Atlantic water fraction in each sub-area is determined from temperature and salinity measurements by using a three-point mixing model [*Hansen et al.*, 2003; *Hughes et al.*, 2005]. Fluxes of volume, heat, and salt of the Atlantic water component through each sub-area are then computed and summed. For the Iceland branch, the inflow area on the section is not sub-divided and the Atlantic water fraction is determined from temperature observations alone (S. Jónsson and H. Valdimarsson, Flow of Atlantic water to the North Icelandic shelf in relation to drift of cod larvae, submitted to *ICES Journal of Marine Science*, 2004, here-

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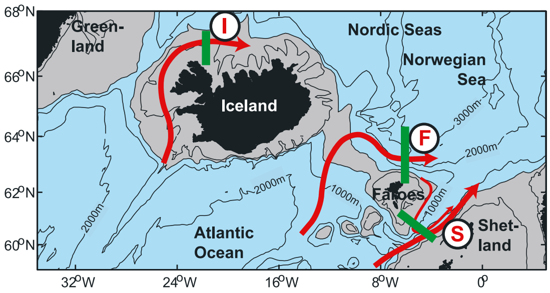

Figure 1. Bottom topography between Greenland and Shetland. Shaded areas are shallower than 500 m. Thick red arrows indicate the three inflow branches: the Iceland branch (I), the Faroe branch (F), and the Shetland branch (S). A thinner red arrow indicates the recirculation in the Faroe-Shetland Channel. Thick green lines show the locations of standard sections along which hydrographic and current data have been obtained.

inafter referred to as Jónsson and Valdimarsson, submitted manuscript, 2004).

3. The Iceland Branch

[8] The flow of Atlantic water along the west coast of Iceland, through the Denmark Strait and into the Nordic Seas has the weakest, although highly variable, volume flux of the three branches. However, it is of great importance to the regional marine climate and hence the ecosystem in North Icelandic waters. The observations were carried out on the Hornbanki section. On this section, CTD profiles have been measured on several standard stations four times a year since 1994 and, during the same period, the inflow of Atlantic water has been monitored by moored current meters. From September 1999, the measurements were extended to three moorings carrying 5 current meters (Figure 2).

[9] The extent of Atlantic water on the section is quite variable. There is usually a core of Atlantic water with salinity above 35, but its position and extent is variable. The Atlantic water does not seem to reach deeper than 200 m (Figure 2) [*Jónsson and Briem*, 2003]. Using observations from this and other sections, Jónsson and Valdimarsson (submitted manuscript, 2004) have determined the Atlantic water fraction within the inflow area of the Hornbanki section (white rectangle on Figure 2) as a function of time and computed fluxes for the 1994–2000 period. The average volume flux of Atlantic water was found to be 0.75 Sv. No seasonal variation was found in current velocities, but the Atlantic water fraction varied seasonally, which gave rise to a seasonal amplitude of 0.2 Sv for the volume flux of Atlantic water with a maximum in September. On daily time-scales, the Atlantic water flux varied from −0.7 to 3 Sv. The blue curve in Figure 5 shows monthly averaged Atlantic water flux within the Iceland Branch since the beginning of 1999 to the end of 2001.

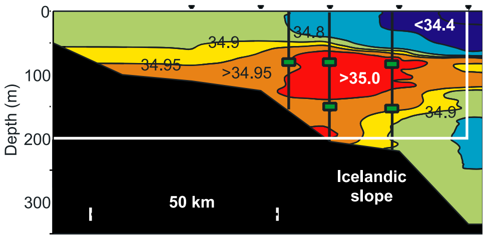

Figure 2. The salinity distribution on a vertical section north of Iceland (green line labelled "I" on Figure 1) in May 2000. The red area marks the core of the Atlantic water defined by the 35.0 isohaline. Green rectangles on vertical lines indicate traditional current meters on moorings since September 1999. Before that, only the central mooring was in operation (since 1994). The white rectangle delimits the area, which is assumed to cover the Atlantic water inflow. Inverted triangles above the section indicate standard CTD station locations.

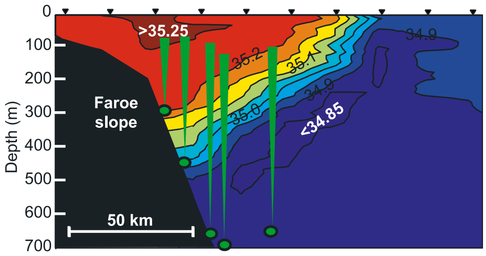

Figure 3. The salinity distribution on a vertical section north from the Faroes (green line labelled "F" on Figure 1) in May 2000. Green circles indicate ADCP's with green cones indicating typical ADCP ranges. ADCP locations shown are for the July 2000–June 2001 period. For the rest of the period analysed, only the innermost and the two outermost ADCPs have been in operation. Inverted triangles above the section indicate standard CTD station locations.

4. The Faroe Branch

[10] The Faroe branch carries the Atlantic water that has passed over the ridge between Iceland and the Faroes. Northeast of the ridge, this water meets the much colder and less saline waters of the East Icelandic Current and gets confined into a fairly narrow current, which flows eastwards over the northern slope of the Faroe Plateau. The observations were carried out on a section crossing the flow. On this section (Figure 3), CTD profiles have been acquired on several standard stations at least four times a year since 1988. From the mid 1990's, ADCPs have been moored on

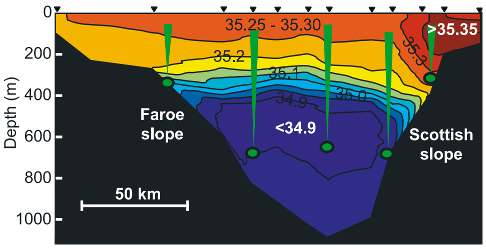

Figure 4. The salinity distribution on a vertical section across the Faroe-Shetland Channel (green line labelled "S" on Figure 1) in July 2000. Green circles indicate long-term ADCP mooring sites and the green cones indicate typical ADCP ranges. The shallowest ADCP on the Faroe slope has not been in operation since summer 2000. Inverted triangles above the section indicate standard CTD station locations.

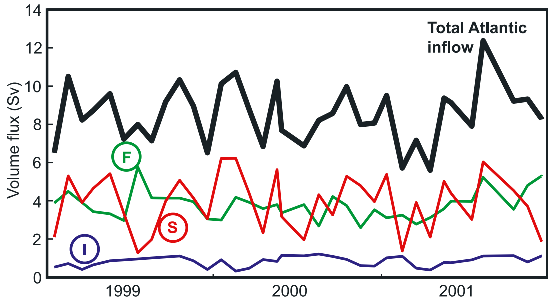

Figure 5. Monthly averaged volume flux of Atlantic water in each of the three branches (coloured lines labelled as the Iceland branch (I), the Faroe branch (F), and the Shetland branch (S)) and in the total Atlantic inflow (black line) for the 1999 to 2001 period.

the section almost continuously. The number and locations of ADCP moorings have varied somewhat, but since summer 1997 there have always been at least 3 and sometimes 5 functioning ADCP's on the section except for annual servicing gaps.

[11] *Hansen et al.* [2003] have analysed the observations from the June 1997 to June 2001 period. On average, the Faroe branch transported a volume flux of 3.5 ± 0.5 Sv of Atlantic water. Monthly averaged volume flux ranged between 2.2 and 5.8 Sv, but with only a very small seasonal variation. Daily averages ranged between 0.3 and 7.8 Sv, with not a single flow reversal during the 4-year period. The green curve in Figure 5 shows monthly averaged Atlantic water flux within the Faroe branch from the beginning of 1999 to the end of 2001.

5. The Shetland Branch

[12] The Shetland branch carries Atlantic water entering the Norwegian Sea through the Faroe Shetland Channel in addition to water re-circulated from the Faroe branch. The observations were carried out on a section crossing the channel south of the Faroes. At least four, and before summer 2000 five, ADCP moorings have been maintained on the section since November 1994. In this period, from four to eight CTD sections were obtained annually.

[13] Combining these observations with ADCP data acquired from oil platforms, *Turrell et al.* [2003] analysed the fluxes through the Channel from 1994 to 2000. On average the Atlantic water flux was estimated at 3.2 Sv with only a small seasonal amplitude of 0.2 Sv and maximum in November. The red curve in Figure 5 shows monthly averaged Atlantic water flux 1999–2001 within the Shetland branch [*Hughes et al.*, 2005].

6. Discussion

[14] Table 1 summarizes the main characteristics of each Atlantic inflow branch as well as the total inflow for the period January 1999 to December 2001 for which we have high-quality simultaneous measurements. The values for the volume fluxes of the various branches differ slightly from previously published values [*Østerhus et al.*, 2001; *Hansen et al.*, 2003; *Turrell et al.*, 2003; Jónsson and Valdimarsson, submitted manuscript, 2004] but the deviations are small and may be due to the different averaging periods.

[15] The differences in characteristics and observational procedures of the three branches make a formal uncertainty analysis for the total flow difficult. For the Faroe branch, *Hansen et al.* [2003] determined the uncertainty of the average volume flux to be on the order of 0.5 Sv. From this, we estimate an uncertainty of about 1 Sv for the average total volume flux of Atlantic water. Our estimate of the total volume flux (8.5 Sv) is close to the preliminary estimate reported by *Hansen and Østerhus* [2000] and also remarkably close to the classical value published by *Worthington* [1970].

[16] Included in Table 1 are the average temperature and salinity of the water transported by each of the inflow branches. Weighting these values with the volume flux of each branch, the average characteristics of the total Atlantic inflow can be determined (Table 1). If these values and our estimate of the volume flux could be combined with similar data for all other branches flowing into or out of the Arctic Mediterranean, accurate freshwater (salt) and heat budgets could be determined.

[17] At present, information from some of these other branches is not sufficient to allow accurate estimates but our values for heat and salt fluxes in Table 1 give some indication. The heat delivered to an area by a current depends not only on its initial temperature, but also on the temperature of the water when it leaves the area. Although not very accurately known, all the outflow branches from the Arctic Mediterranean have average temperatures close to 0°C and the value for total heat flux listed in Table 1 should therefore be fairly close to (order of 10%) the real value for the oceanic heat flux into the Arctic Mediterranean. This number may appear small compared to the atmospheric heat transport but its effect on the climate of the Arctic is still very significant [*Seager et al.*, 2002].

[18] For the 1999–2001 period with concurrent measurements, the Iceland branch was found to carry 10% of the Atlantic inflow volume flux with the other two branches

Table 1. Characteristics of Each of the Three Atlantic Inflow Branches and of the Total Inflow for the Period January 1999 to December 2001[a]

	Average Fluxes							
Inflow Branch	Vol., Sv	Heat, TW	Salt, kT·s^{-1}	Average Temp., °C	Average Sal.	Seasonal Vol. Flux, Sv	Seasonal Vol. Flux Max.	P
Iceland	0.8	22	(30)	6.0	$\leq$35.00	0.2	Sep	<0.01
Faroe	3.8	134	133	8.2	35.23	0.3	Oct	n.s.
Shetland	3.8	156	139	9.5	35.32	0.2	Mar	n.s.
Total	**8.5**	**313**	**303**	**8.5**	**35.25**	**0.4**	**Oct**	**n.s.**

[a] The three last columns show the seasonal amplitude, the time (month) of maximum Atlantic water flux, and the probability (P) that the seasonal amplitude is zero (n.s. means not significant). Heat flux is relative to 0°C. Units are: Sv = 10^6 m^3·s^{-1}, TW = 10^{12} W, kT·s^{-1} = 10^6 kg·s^{-1}.

carrying 45% each. Since temperature and salinity increase towards the southeast, the Shetland branch carried a slightly larger fraction of the salt (46%) and a considerably larger fraction (50%) of the heat flux, although this number depends on the chosen reference temperature (0°C).

[19] Monthly averaged volume fluxes for each branch and for the total inflow are shown in Figure 5 for a three-year period. Although they are of similar intensity on the average, Figure 5 indicates larger variations in the Shetland branch than in the Faroe branch. It is not clear whether this reflects reality or indicates differences in precision of the estimates. Certainly, the Shetland branch is more difficult to monitor accurately due to the recirculation in the Faroe-Shetland Channel and the intensity of meso-scale activity.

[20] Fitting the monthly flux values to a sinusoidal seasonal curve, only the Iceland branch was found to have a seasonal amplitude significantly different from zero (Table 1). The Faroe branch and the Shetland branch had small, non-significant, amplitudes and were out of phase. As could be expected, therefore, the total inflow was found to have a seasonal amplitude of only 0.4 Sv (5% of the average), which was not significantly different from zero (Table 1).

[21] This might appear to conflict with reports of considerably larger seasonal variations in the Norwegian Atlantic Current on the Svinøy section, downstream from our observations [*Orvik et al.*, 2001]. However, they only had long-term direct current measurements from the inner branch of this flow and the outer branch has been reported to vary in counter-phase to the inner branch [*Mork and Blindheim*, 2000]. The observation of strong seasonality in the inner branch of the Svinøy section is therefore not inconsistent with a relatively weak seasonality of the total Atlantic inflow and may be explained by winter intensification of the flow at the Svinøy section due to spin-up of the local basin gyres [*Jakobsen et al.*, 2003].

[22] In a study, using a numerical ocean model forced by NCEP/NCAR re-analysis data, *Nilsen et al.* [2003] have reported fairly strong correlations between variations of inflow fluxes of the different branches with, e.g. the Faroe branch and the Shetland branch being negatively correlated. They considered low-pass filtered fluxes with a cut-off period of 3 years, which we cannot reproduce with our observations. If we compute annual mean fluxes for the 1999–2001 period, we do see a similar tendency but with only three years of simultaneous data, its significance is questionable. The tendency seems, however, to persist on seasonal timescales. Using 3-month averaged Atlantic inflow volume flux, the Shetland branch was found to be negatively correlated with the Faroe branch ($r = -0.52$) and with the Iceland branch ($r = -0.58$), whereas a small positive correlation ($r = 0.32$) was found between the Faroe branch and the Iceland branch. The numbers are still too small to ensure significance in a statistical sense but these correlation coefficients are comparable to the values reported by *Nilsen et al.* [2003].

[23] A negative correlation between the Shetland branch and the other two branches would tend to reduce variations in the total Atlantic inflow and may explain its apparent stability. In the 1999–2001 period, the total Atlantic inflow volume flux ranged between 8.3 and 8.7 Sv on an annual average and between 7.5 and 9.9 Sv on a 3-month average. On these timescales, total inflow to and total outflow from the Arctic Mediterranean have to balance fairly well to prevent large sea-level changes. Most of the outflow occurs as deep overflow, which presumably has time-scales of many years. This can be expected to act as a constraint on the effect of wind stress forcing on the total Atlantic inflow and tend to reduce the inflow in one branch if another inflow branch experiences a wind-induced intensification, leading to a negative correlation between the branches, as observed.

[24] In conclusion, it may be noted that the established observational system has been able to produce consistent flux estimates. Clearly, the accuracy of these estimates can be improved by increased resources and, especially for the Shetland branch, a denser net of moorings. Lack of knowledge on features and processes affecting the inflow also limits the accuracy, however, and once these have been better clarified, it may well become possible to re-evaluate the existing data sets and achieve more accurate flux estimates. In the meantime, the observations are planned to be continued to increase our knowledge about the natural variability of the Atlantic inflow and to allow early warning, if global change were to induce a weakening of this integral part of the Atlantic thermohaline circulation as some climate models predict.

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