ICES Journal of Marine Science, 62: 1350–1359 (2005)
doi:10.1016/j.icesjms.2005.05.003



# The flow of Atlantic water to the North Icelandic Shelf and its relation to the drift of cod larvae

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Jónsson, S., and Valdimarsson, H. 2005. The flow of Atlantic water to the North Icelandic Shelf and its relation to the drift of cod larvae. – ICES Journal of Marine Science, 62: 1350–1359.

The amount of Atlantic water (AW) present on the shelf north of Iceland is highly variable and influences the local biological productivity. Estimates of the volume and heat transports of AW to the North Icelandic Shelf between 1994 and 2000 are presented here. On average, 66% of the eastward flow on the Hornbanki section consists of AW with a transport of AW of approximately 0.75 Sv. The associated heat transport is 19 TW. There are large interannual variations in the transports, from over 1 Sv in the summers of 1997, 1999, and 2000 to almost no AW transport in February/March 1995. The seasonal variation in the transport has an amplitude of 0.2 Sv with a minimum in February/March and maximum during late spring and summer. Larval cod are carried by this flow from the main spawning grounds south of Iceland to the nursery grounds on the North Icelandic Shelf. The increasing abundance and the better condition of cod larvae after 1997 are related to the increase of the AW inflow then.



Keywords: Atlantic water, climate, cod larvae, Denmark Strait, Nordic Seas, North Icelandic Irminger Current.

Received 21 January 2005; accepted 3 May 2005.

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## Introduction

The flux of Atlantic water (AW) and the associated heat transport across the Greenland–Scotland Ridge is an important factor for the climate in the area north of the ridge. This flux occurs in three different branches, the Faroe–Shetland Current west of the Shetland Islands (Turrell *et al.*, 2003), the Faroe Current north of the Faroes (Hansen *et al.*, 2003), and the North Icelandic Irminger Current north of Iceland. The North Icelandic Irminger Current is the weakest, has the lowest temperature and salinity, and shows the greatest relative variability of the three. The AW flows towards Iceland with the North Atlantic Current, and part of it flows as the Irminger Current along the south and west coasts of Iceland. South of the Denmark Strait the current bifurcates, with the main branch turning west towards Greenland while a small branch continues northward and flows into the North Icelandic Shelf area as the North Icelandic Irminger Current. After that, the current is mainly confined to the shelf (Stefánsson, 1962). This flow of AW along the west coast of Iceland and onto the North Icelandic Shelf is of great importance for the ecosystem there. It is rich in nutrients and creates conditions favourable for phytoplankton and zooplankton growth (Ástthórsson *et al.*, 1983; Thórdardóttir, 1984). It has also been shown that this flow has a positive influence on the weight of capelin north of Iceland (Vilhjálmsson, 1997), which is an important source of food for the Icelandic cod stock. The amount of AW present on the shelf north of Iceland is highly variable, causing changes in the conditions for the flora and fauna (Malmberg and Valdimarsson, 2003).

The main spawning grounds for Icelandic cod are on the shelf southwest of Iceland. The eggs and larvae mainly drift clockwise around the country and eventually reach the nursery grounds off the north coast. Recently, it was shown that spawning also occurs to some extent in the fjords on the west, north, and east coasts, and the success of the spawning in the south and west seems to depend on how effectively the flow of AW to the North Icelandic Shelf transports the eggs and larvae to the nursery grounds that lie mainly off the north coast (Begg and Marteinsdottir, 2000).

In view of the flow's importance, the Marine Research Institute has been monitoring the inflow of AW with current meters on the Kogur section from 1985 to 1994 and on the Hornbanki section since 1994. The region of study is shown in Figure 1. In this paper we estimate the mean and variability in the volume and heat transport of AW based on the current meter data augmented by hydrographic information. We also investigate the relationship between the AW inflow and 0-group cod.

## Data

Since 1985, the Marine Research Institute has been monitoring the inflow of AW onto the North Icelandic Shelf using Aanderaa current meters on one mooring. From 1985 to 1994, the mooring was situated close to the Kogur section (Kogur in Figure 1), after which it was moved close to the Hornbanki section at H2 with current meters at 80-m and 150-m depth (Figures 1 and 2). Measurements from the Kogur mooring station were described by Kristmannsson (1998), while in this paper, only the data from Hornbanki will be discussed. In September 1999, the measurements were extended to three moorings with a total of five instruments (H1, 80 m; H2, 80 m and 150 m; and H3, 80 m and 150 m; Figures 1 and 2). During the period of current meter measurements from September 1999 until August 2000, hydrographic observations were taken along the Hornbanki section (Figure 1) five times using a CTD. Usually the section consists of five stations numbered as shown in Figure 2. Temperature and salinity data used in water mass analysis were taken from Stations LB6 and KG6 from the Latrabjarg and Kogur sections, respectively (Figure 1).

Annual 0-group cod surveys have been carried out in August from 1970 to 2003. From these surveys, an abundance index is estimated, and the lengths of the 0-group cod measured.

## Results

### Transport of AW and heat in the period September 1999–August 2000

Figure 2 shows the distribution of salinity on the Hornbanki section during the five occupations between September 1999 and August 2000. While the position and extent of the core of the AW (salinities $>35$) vary, the core is usually between hydrographic Stations 2 and 4, where current meters were positioned. CTD data indicate that the AW does not reach deeper than 200 m, below which colder and less saline water from the Iceland Sea is present. This depth will be used as the lower boundary for the AW.

Although the outer boundary of the flow of AW probably varies in time, we have taken it to coincide with hydrographic Station 5 (67°20′N), for the following reasons. First, when the CTD measurements extended farther north (which occurred several times since 1994, although not all the sections are shown), AW was not found

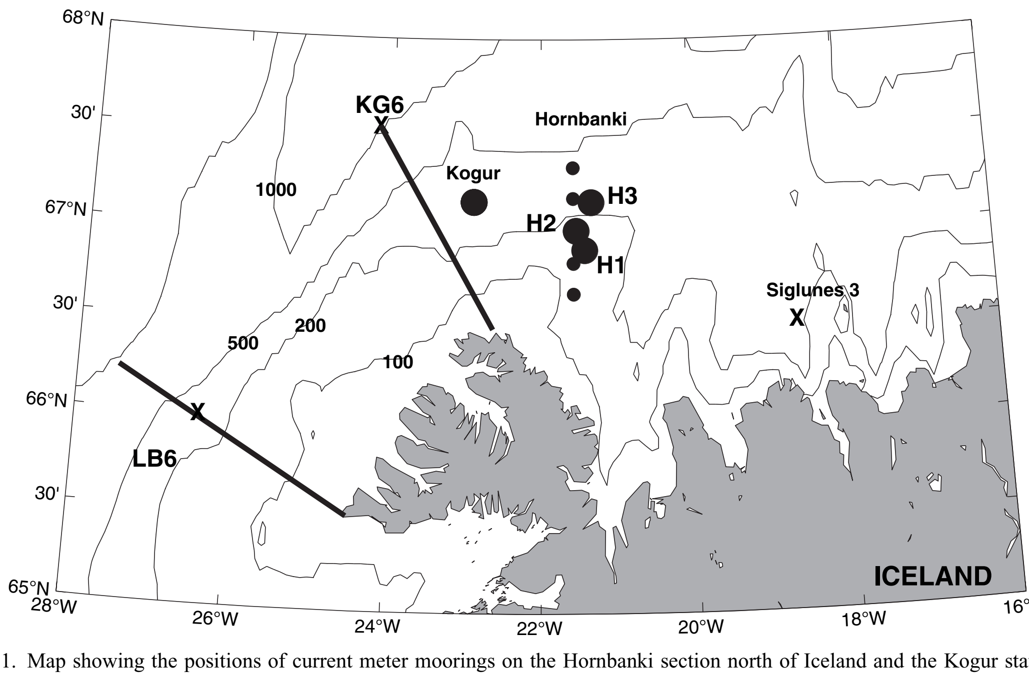


Figure 1. Map showing the positions of current meter moorings on the Hornbanki section north of Iceland and the Kogur station (large dots). Hydrographic stations on the Hornbanki section are shown as small dots and standard CTD sections Latrabjarg and Kogur are shown as straight lines. Depth contours are 100, 200, 500, and 1000 m.

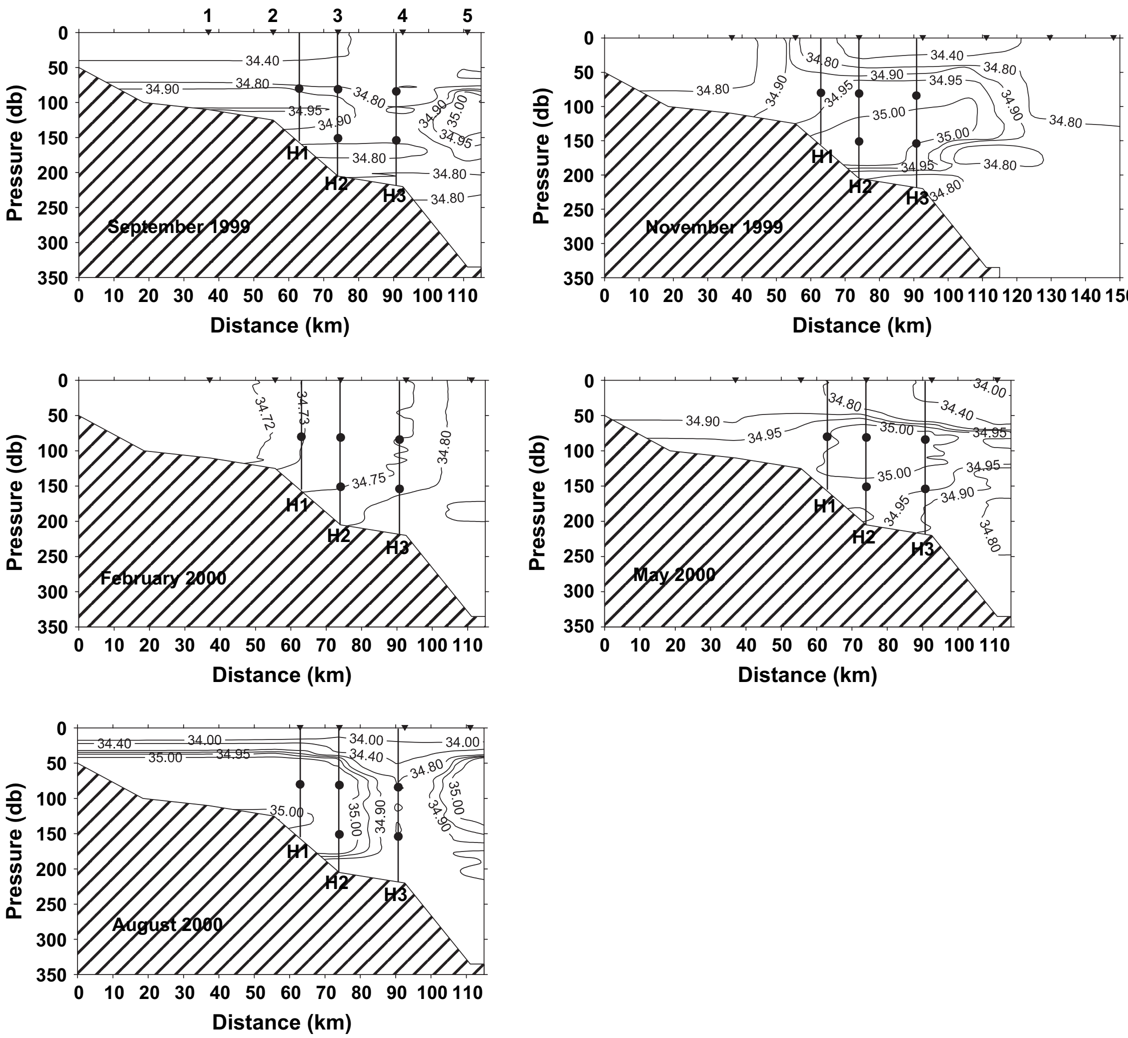


Figure 2. The salinity on the Hornbanki section north of Iceland in 1999–2000. Also shown are three moorings on the section as well as CTD stations with increasing numbers from the coast.

beyond Station 5. Second, measurements with a vessel-mounted ADCP indicate that an appropriate termination point for the AW flow is at about 67°20′N (Figure 3). Third, there is a strong westward current over the slope with a core at 67°30′N carrying water towards the Denmark Strait (Jónsson and Valdimarsson, 2004; Figure 3). Finally, data from drifters drogued at 15-m depth and deployed on the shelf south and west of Iceland in the years 1995–1998 can also be used to estimate the spatial distribution of the inflow of AW to the North Icelandic Shelf (Figure 4). The figure, restricted to observations with a positive eastward component of the velocity, shows that these were mostly confined to the region south of 67°20′N. Drifters that enter further north show a tendency to be entrained into the westward flow (Valdimarsson and Malmberg, 1999; Jónsson and Valdimarsson, 2004).

It can be argued that the fresher water seen close to the shore is AW that has been diluted by freshwater run-off from land. In February 2000, there is no identifiable core of AW, and the waters are well mixed. Even though there is no water with distinct Atlantic character, the water that is present is considered a mixture of AW, run-off from land, and colder, less saline water from the north. Thus, when calculating the transport in this study, the AW current is delimited by 67°20′N and the coast, and lies above 200-m depth.

The current is highly barotropic at both current meter Stations H2 and H3 (Jónsson and Briem, 2003) and along the Hornbanki section based on vessel-mounted ADCP measurements (Figure 3). This is in agreement with the findings of Kristmannsson (1998) at the Kogur station. For estimating the transport, the current at 80-m depth is

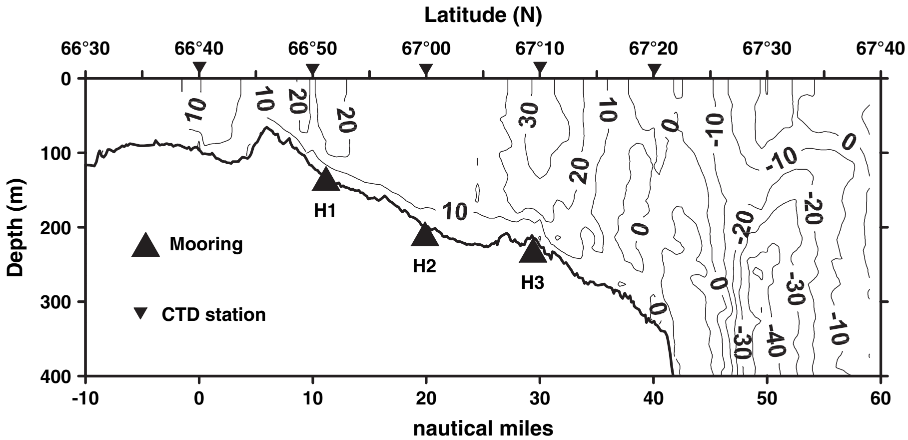


Figure 3. The average of the E–W component (positive toward east) of the current measured with a vessel-mounted ADCP at the Hornbanki section in November 2002 in $10^{-2}$ m s$^{-1}$. Negative values over the slope indicate a current toward the west.

therefore assumed to be representative from 0 to 115 m and the current at 150 m from 115 m to the bottom or to 200-m depth, whichever is less. At H1, the current at 80-m depth is assumed to be representative of the whole water column.

It has been shown that the monthly mean current, almost without exception, increases with distance from the shore (Jónsson and Briem, 2003). This is especially evident during spring and summer when the highest values are observed at the outermost mooring. Inshore of H1, ADCP measurements also indicate a decrease of the current towards the shore (Figure 3). It is therefore assumed in the transport estimates that the velocity decreases linearly from the innermost mooring to 0 m s$^{-1}$ at 66°20′N, which is where the plots of the hydrographic sections in Figure 2 start. South of that point, there are rather shallow areas towards the shore.

A proportional area is assigned to each current meter and then multiplied by the velocity perpendicular to it to obtain the total volume transport through the section. To obtain the flux of AW, it is necessary to distinguish the water masses flowing across the section to obtain the proportion of AW present on the section. This should be the flow that is relevant when considering the drift of cod larvae from the spawning areas southwest of Iceland. It is also important from a climatic perspective, since it is the flow that brings the high heat and salt fluxes from the south.

One way to estimate the water mass composition would be to use the CTD sections, but there is not much continuity in time between the CTD data from one section to the other. The CTD data can be compared with temperature data measured at the current meters shown in Figure 5. There is considerable short-term variability in the temperature, as measured by the current meters, that is not picked up by the CTD sections. For example, the temperature at all current meters fell by almost 3°C from the time the CTD section was taken in mid-November 1999 until the end of that month. Because of the great temporal variability in the water masses present on the section, the CTD data from the Hornbanki section are not directly useful for determining the proportion of AW present on the section at other times. In view of this, the proportion of AW present was determined assuming that the temperature measured at each current meter was the result of Polar Water (PW), coming from the north with the East Greenland Current, mixing with AW coming from the south. Since the AW and PW characteristics also vary, properties for these water masses were taken from Stations LB6 and KG6 (Figure 1). These two stations, where CTD measurements were taken four times each year, are always embedded in AW and PW, respectively (Figure 6), although the KG6 station is not always accessible since it may occasionally be covered with sea ice. For calculating the proportions of the two water masses at the current meter sites, the available data at 80-m depth from LB6 and KG6 were each fitted with a sinusoid, simulating the seasonal cycle plus a linear trend as the AW was warming and the PW was becoming colder. These together with data from H2 at 80-m depth are shown in Figure 6. The temperature at H2 almost always was between the estimated AW and PW temperatures. If it was above or below, the proportions of AW were set to 100% and 0%, respectively. Similarly this was done for 150-m depth and for all the current meters. Thus, the fraction of AW at each instrument was calculated. These fractions were multiplied by the volume transport associated with each instrument and then summed to obtain the total transport of AW on the North Icelandic Shelf. The heat transport was calculated relative to 0°C, and only the AW portion of the flow was included as well as the temperature of the pure AW. This procedure was used for estimating the transport of AW for the period when five current meters were available, i.e. from September 1999 to August 2000. The monthly means of the volume transport of AW are shown as open circles in Figure 7. The average transport of AW during this period was 0.84 Sv (1 Sv = $10^6$ m$^3$ s$^{-1}$),

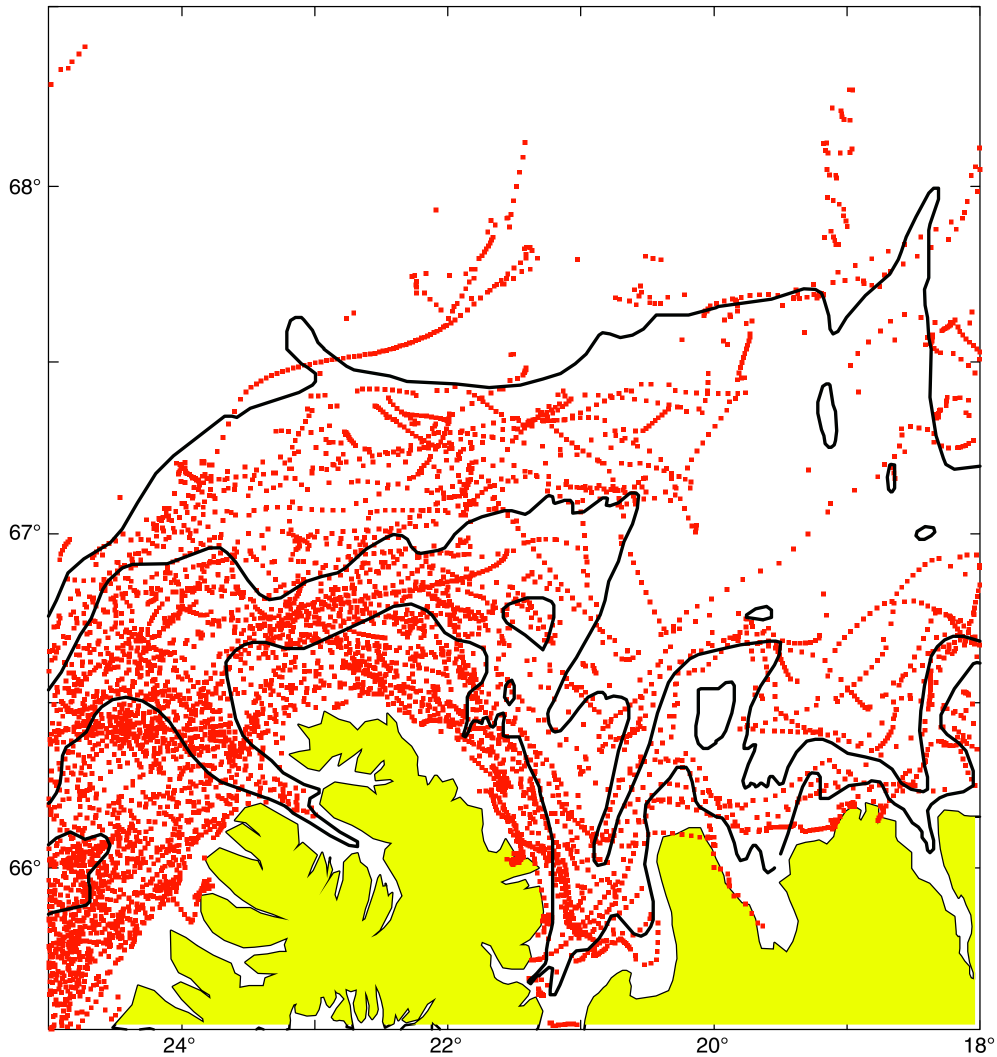


Figure 4. Data from drifters drogued at 15-m depth that were deployed on the shelf south and west of Iceland in the years 1995−2000. Each data point represents a 6-h subsampled location of a drifter. The points are not trajectories but only show observations with a positive eastward component of velocity.

comprising 67% of the total flow, and the associated heat transport was 22 TW (TW $= 10^{12}$ W).

## Interannual variability

Current measurements have been made almost continuously at H2 (80 m) since September 1994, and can be used to study the interannual variability of the flow of AW along the shelf. Results for 1999−2000, when three moorings were available, were used to extrapolate to the years when only one mooring was present using regression analysis. The temperature and the velocity at each of the sites were estimated from the temperature and velocity at 80 m at H2, and this was used to calculate the monthly volume and heat fluxes of AW (Figure 7). For comparison, the 1999−2000 estimates based upon all five current meters are also shown in Figure 7. There is almost no difference in the average transport for this period using all five instruments compared with the single measurement at H2, but the former gives slightly larger transports during spring and summer, but less during winter. This is believed to be due to the higher currents during spring and summer at H3, which are not seen at the other mooring sites (Jónsson and Briem, 2003).

The average transport of AW for the whole period in Figure 7 is 0.75 Sv, and the corresponding heat transport associated with the AW flow is 19 TW. For the whole period the proportion of AW in the section was 66%.

There are basically three sources of uncertainty associated with the volume transport estimates, and they are all difficult to evaluate. First, there is uncertainty associated

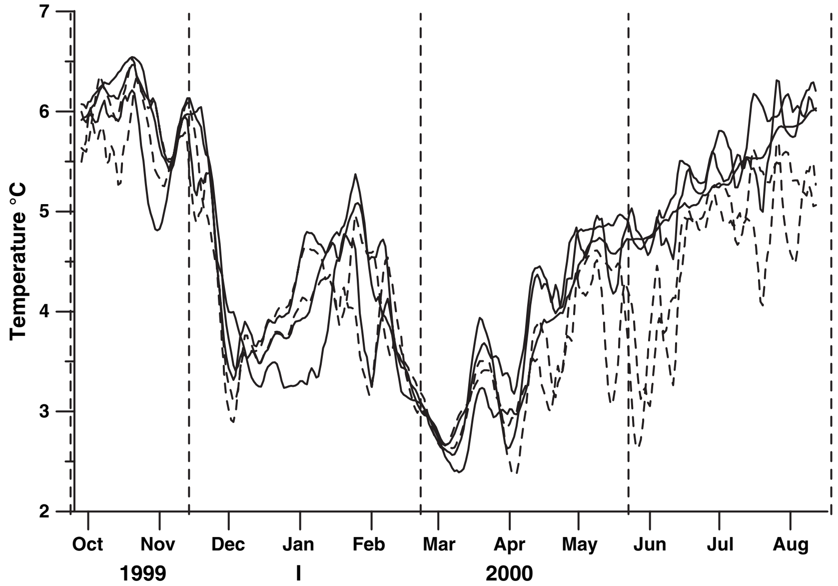


Figure 5. The temperature at the current meters in 1999–2000. Solid curves are from 80-m depth at H1, H2, and H3, and dashed curves are from 150-m depth at H2 and H3. Dashed vertical lines indicate the times when the CTD sections were taken. Ticks indicate the beginning of each month.

with the determination of the water mass fractions. The northernmost possible Station LB6 was assumed to always be in pure AW and Station KG6 in pure PW. These assumptions are reasonable, however, and the associated errors are considered to be very small. Second, there is uncertainty associated with the interpolation and extrapolation of the currents from the current meters. Since the current is mostly barotropic and there are significant correlations horizontally, there is no reason to believe that there are large uncertainties in the estimate of the currents over the area assigned to each current meter. Finally, there is the uncertainty of the area covered by the flow, and this is believed to be the main source of uncertainty. Using all the information provided here, such as the salinity sections, the

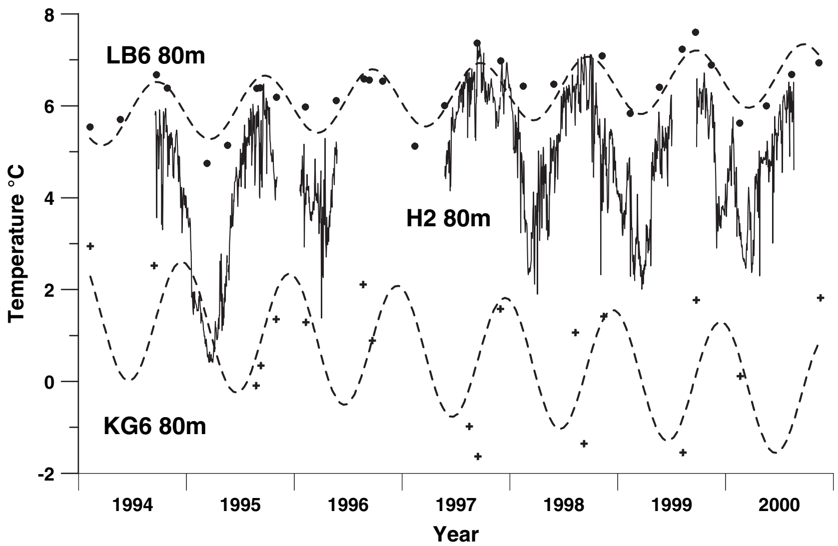


Figure 6. The 80-m temperatures at Latrabjarg Station 6 (dots) and Kogur Station 6 (crosses) and the sinusoidal fits to those measurements. The solid line is the 80-m temperature at H2.

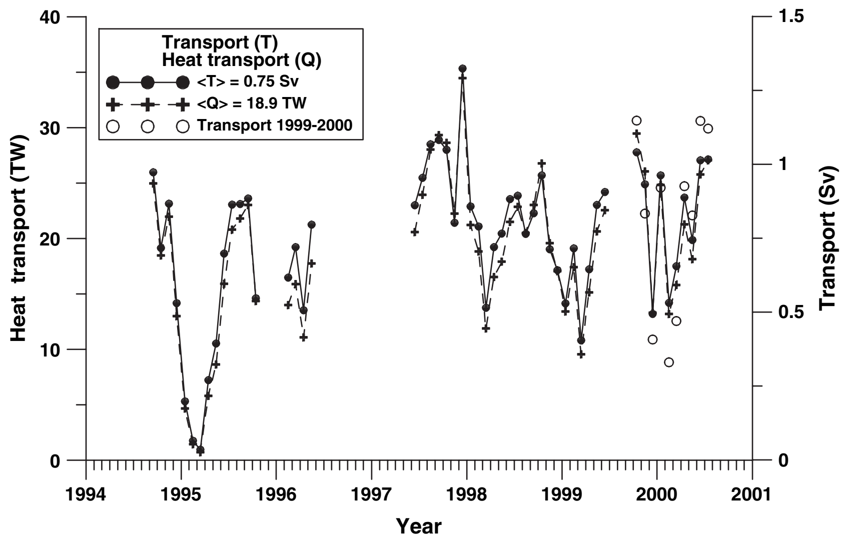


Figure 7. Monthly values of the volume and heat transport of AW. Open circles indicate the volume transport of AW using all five current meters available in 1999–2000.

ADCP section, and the drifter data, the uncertainty is thought to be of the order of 20%. Thus, the estimate of the average volume transport of AW is 0.75 $\pm$ 0.15 Sv.

Large interannual variability in the transports is present in the record (Figure 7). Especially interesting is that the AW is almost absent in the section in February and March 1995, and it remained small until June, when the flow of AW recovered. This lack of AW was also observed in the hydrographic conditions in spring on the North Icelandic Shelf (Malmberg and Jónsson, 1997).

## Seasonal variations

There are seasonal variations in the flux of AW, as illustrated in Figure 8. The amplitude of the variations is about 0.2 Sv, with a minimum during February/March and maximum in summer. This is true both for the 1999–2000 period and for the total data set when all available data for each calendar month are averaged. These seasonal variations in the transports are similar to those proposed by Stefánsson (1962). He attributed this increase in transport to the influence of freshwater run-off from land that would increase the baroclinic current over the shelf. If true, the current would be expected to increase towards the coast. However, the measurements presented here and also discussed in Jónsson and Briem (2003) indicate that this is not the case and that the increase in speed occurs at the outermost mooring. The ADCP measurements shown in Figure 3 also indicate that the current decreases as the shore is approached. Jónsson and Briem (2003) showed that the monthly mean current almost always decreased when approaching the coast, a result consistent with drifter data (Valdimarsson and Malmberg, 1999). Therefore, it is probably not the freshwater run-off from land that causes the seasonal variations in transport. A more likely cause is atmospheric forcing that is much stronger in winter than during summer. In this area, northerly winds are frequent in winter (Einarsson, 1976). These winds oppose the AW flow along the west coast of Iceland and could reduce the inflow of AW to the North Icelandic Shelf. It has been found that the hydrographic conditions on the North Icelandic Shelf are indeed influenced by local wind in the area (Stefánsson and Guðmundsson, 1969; Ólafsson, 1999).

## Drift of cod larvae and the AW

The 0-group abundance index for cod is shown in Figure 9 together with the mean length of the juveniles. Spawning on the main spawning grounds off the southwest coast occurs earlier than the local spawning in the fjords on the north coast (Marteinsdottir *et al.*, 2000). As well as being spawned earlier, larvae originating from the main spawning grounds experience higher temperatures than larvae from the local spawning off the north coast. Thus, larvae from the main spawning grounds are likely to be larger than the ones from the local spawning. Therefore, a larger mean length is assumed to indicate that the larvae originate from the main spawning grounds and drift with the AW to the North Icelandic Shelf. Also included in Figure 9 is the 0–100 m salinity at Station Siglunes 3 (Figure 1), as measured in May and August and averaged for the 2 months. This is considered representative of the salinity that larvae experience prior to settlement and the strength of the flow of AW to the shelf during this period. Salinity on the North Icelandic Shelf is also well correlated with the temperature (Malmberg and Valdimarsson, 2003). Since salinity is a more conservative parameter than temperature, and temperature measurements are not always made at exactly

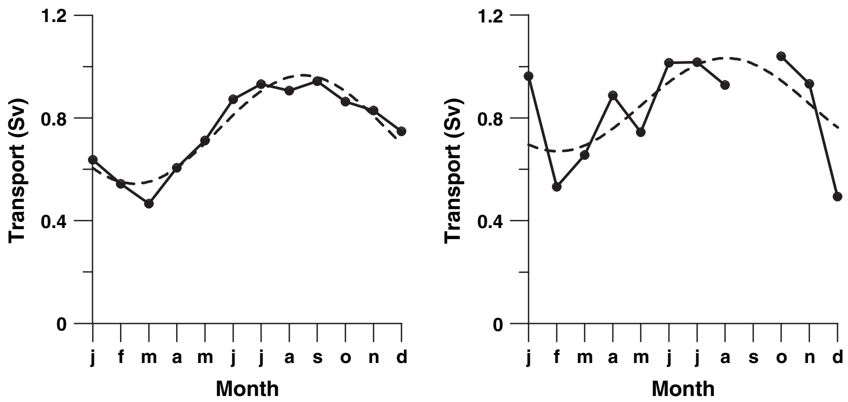


Figure 8. Mean seasonal variations in the AW volume transport for 1994–2000 (left) and 1999–2000 (right). A sinusoidal fit is also shown.

the same time each year, it is preferable to use salinity instead of temperature. If salinity had been measured at the current meters, we would have used it instead of temperature as a measure of the AW.

Although not a perfect fit, there is a resemblance between salinity and the 0-group measures. It is especially evident in 1997 when the 0-group index, as well as the mean length of the juveniles, rose and remained high until 2003, while both were very low in 1995 and 1996.

From 1997, the flow of AW has been stronger and salinity has been higher than it was in 1994–1995. The average transport of AW in the 1994–1995 period was 0.56 Sv and 51% of the total flow, while for the period 1997–2000 the average transport was 0.84 Sv and 68% of the total. The corresponding heat transports were 14 and 22 TW, respectively. Thus, there was 50% more AW and 57% more heat flowing into the North Icelandic Shelf area during the latter period than during 1994–1995. Drifters deployed on the main spawning sites indicate that it takes juveniles 2–3 months to reach as far as the Hornbanki section (Valdimarsson and Malmberg, 1999) so the larvae should be drifting across the Hornbanki section during spring and early summer. Similar values were found when calculating the same ratios for the AW and heat flow as above for this period of the year. The trend of increasing influence of AW in the late 1990s is reflected in the hydrographic variations seen on the North Icelandic Shelf (Figure 10). Low salinities were observed in spring 1995 and 1996, and in both those years the 0-group index was very low. The most pronounced distribution of high salinity

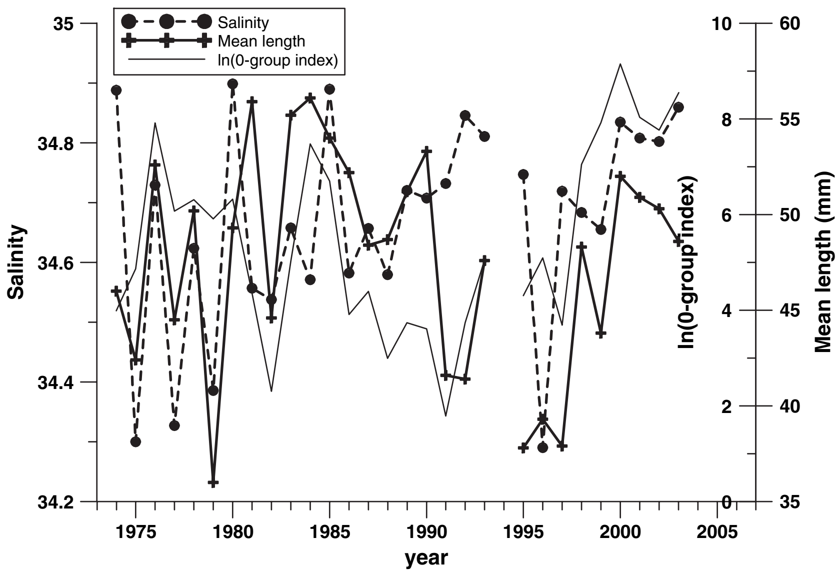


Figure 9. The 0-group index for cod together with the mean length of the juveniles. Also shown is mean salinity (0–100 m) as measured at Station Siglunes 3 (Figure 1) in May and August and averaged for the 2 months. Only data when all parameters are available are shown.

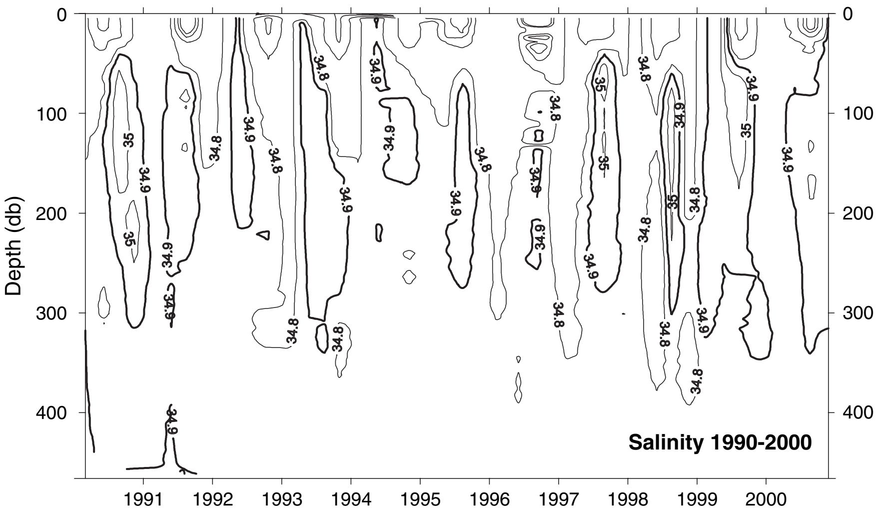


Figure 10. Time-series of salinity from the Siglunes 3 station on the central North Icelandic Shelf from 1990 to 2000. Salinity contours are shown for every 0.1 between 34 and 35.

AW was observed during 1999, when a record 0-group index was observed.

During the early 1990s especially, there was a lack of correspondence with high salinities over the North Icelandic Shelf without a strong 0-group. This might be related to poor recruitment from the small spawning stock that also consisted mostly of young fish (Marteinsdottir and Thorarinsson, 1998). It is clear that factors other than environmental can also affect the outcome of spawning, and it is therefore not to be expected that a single variable will always control 0-group abundance.

## Discussion

Transport estimates of AW on the North Icelandic Shelf presented here are the first such estimates based on more than one current meter mooring. This flux is important both for the hydrographic conditions on the shelf north of Iceland and also for the biological resources in the area. It is also of interest from a climatic perspective, since this is one of the three branches carrying AW to higher latitudes across the Greenland−Scotland Ridge. Transport of AW and heat by the other two branches, the Faroe Current and the Faroe−Shetland Current, have been reported by Hansen *et al.* (2003) and Turrell *et al.* (2003) to be 3.5 Sv (124 TW) and 3.2 Sv (123 TW), respectively. The volume flux of AW northwest of Iceland is then about 10% of the total volume flux of AW to the Nordic Seas and the heat flux is about 7% of the total heat flux with the AW to the Nordic Seas.

The amplitude of the seasonal variation found here is of similar absolute magnitude to the seasonal variations found in the Faroe−Shetland Current (Turrell *et al.*, 2003), but in the Faroe Current, Hansen *et al.* (2003) found no significant seasonal variation. In the Faroe−Shetland Current there was a maximum in autumn and a minimum in spring, whereas a maximum is found in the North Icelandic Irminger Current during late spring and summer.

The estimate for the average flow of AW to the North Icelandic Shelf presented here is only about half of the 1.5 Sv estimated by Kristmannsson (1998) for the Kogur section for the period 1985−1990. Kristmannsson had only one mooring and might therefore easily have overestimated the current, since it is evident from the data presented here that the current is not horizontally homogeneous. Some of the AW present at the Kogur section might also recirculate and return to the west before it reaches the Hornbanki section.

Since 1997, favourable conditions with stronger flow of AW than in 1994−1995 have prevailed off the north coast. These changes in the transport have been consistent with the conditions on the shelf north of Iceland where AW has been present in greater quantities from 1997 to 2000. This has probably provided good conditions for the growth and drift of larvae from the spawning grounds south of Iceland to the nursery grounds off the north coast.

## Acknowledgements

The observations and the work reported here have been funded partly by the Icelandic Research Council "The Environmental Research Programme of the Nordic Council of Ministers (NMR) 1993−1998 (Nordic WOCE project)", by the EU-MAST4 (VEINS project), and from the ongoing EU project MOEN under contract Nr. EVK2-CT-2002-000141. We thank our colleagues at the Marine Research Institute for valuable discussions and help with the fieldwork and data processing.

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