

Direct measurement of volume flux in the Faroe-Shetland Channel and over the Iceland-Faroe Ridge

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[1] Determining the exchange of water across the Iceland-Faroe-Scotland ridge is of fundamental interest because it measures the rate of transformation of North Atlantic water into dense water and thus the strength of the meridional overturning circulation (MOC). Here we study this exchange by monitoring all water flowing through the area east of Iceland to near the bottom or ~ 600 m depth using a 75 kHz acoustic Doppler current profiler (ADCP) mounted on the high-seas ferry M/F Norröna. Starting in March 2008, currents have been measured in the Faroe-Shetland Channel (FSC) and along the Iceland-Faroe Ridge (IFR) on the ferry's weekly round-trips between Iceland and Denmark. The detided average transports (to the north) across the two sections are 4.1 ± 0.1 Sv ($10^6 \text{ m}^2 \text{ s}^{-1}$) through the FSC and 4.4 ± 0.25 Sv across the IFR (this excludes ~ 1.6 Sv circulating around the Faroes). The Norröna program is ongoing. **Citation:** Rossby, T., and C. N. Flagg (2012), Direct measurement of volume flux in the Faroe-Shetland Channel and over the Iceland-Faroe Ridge, *Geophys. Res. Lett.*, 39, L07602, doi:10.1029/2012GL051269.

1. Introduction

[2] The transport of water from the North Atlantic to the Nordic Seas is of great interest because it offers an accurate measure of the production of dense water that flows back out into the global ocean as part of the global meridional overturning circulation (MOC). Following the seminal study by *Helland-Hansen and Nansen* [1909] of the Norwegian Sea, much attention has been given to the strength of the Slope Current in the Faroe-Shetland Channel (FSC). It is of more than historical interest to note that their 4 Sv inflow is close to modern estimates [*Hansen and Østerhus*, 2000; *Hansen et al.*, 2008; this study]. Attention to the inflow of North Atlantic water between Iceland and the Faroes developed later such that the first carefully considered estimate is probably the 3.3 Sv estimate shown in Figure 8 of *Hansen and Østerhus* [2000]. They note the challenges of estimating fluxes using the dynamic method without adequate reference velocity information, which is made even more challenging given the presence of strong bottom flow over complex topography [*Østerhus et al.*, 2008]. An alternative approach to measuring transport is repeated sampling of the currents using an Acoustic Doppler Current Profiler (ADCP) mounted on a vessel in regular service across the sections.

The high horizontal resolution and repeat sampling are the major strengths of vessel-mounted ADCPs. The lack of temporal resolution matters less than building up degrees of freedom to average out the energetic tidal and variable mesoscale eddy field. We report here on the results from the first three years of monitoring the fluxes through these two passages.

2. Data Collection and Analysis

[3] The methodology used to collect the velocity data follows closely that developed by *Flagg et al.* [1998]. The 165 m long and 35,000 GT high seas ferry M/F Norröna is equipped with a 75 kHz RDI Ocean Surveyor ADCP located in the hull 55 m from the bow. Due to frequent high seas and swell, bubble sweep-down is a serious problem. To reduce their impact, the ADCP is located in a streamlined fairing that extends 0.2 m below the hull. In addition, two chines act as vortex generators to produce an uplift of water from about 0.5 m below the hull. These have substantially improved the performance of the system, but the data returns are still limited in wintertime, especially along the Iceland-Faroe Ridge (IFR). Further improvements are planned.

[4] The ADCP operates in the narrow-band mode to profile as deep as possible, ~ 600 m, although the data returns drop rather sharply beyond ~ 500 m depth. For our analysis the single ping profiles are averaged every 3 minutes to provide along track sampling of currents every 3 km (at a vessel speed of 20 Kt) with a vertical resolution of 16 m. The stated single ping accuracy of the 75 kHz ADCP operating with a vertical bin of 16 m is 0.17 ms^{-1} (http://www.rdinstruments.com/datasheets/ocean_surveyor_ds_lr.pdf). With typically 53 pings for each 3-minute ensemble average, the uncertainty is expected to be $\pm 0.02 \text{ ms}^{-1}$. A Thales ADU-5 with 10 m antenna separation (8 m fore-aft and 14 m port-starboard) provides vessel heading once per second with an accuracy 0.03°T , which at 20 Kt translates into a cross-track error of $\sim 0.005 \text{ ms}^{-1}$. All data are available at <http://po.msrb.sunysb.edu/Norröna/>, which also gives a detailed discussion of the technical difficulties dealing with the bubble problem.

[5] Tidal currents in the FSC and over the IFR are significant [*Allen*, 1995; *Larsen et al.*, 2000] and have the potential to contaminate estimates of mean currents, eddy variability and transports. One approach is that with sufficient data collected at random times relative to the tides, the tidal fluctuations would average out. That definitely seemed to be the case in the more densely sampled FSC but with less data available for the IFR section there was a greater potential for contamination. Thus, we have attempted to remove the principal tidal components (M2, N2, S2, L1 and O1) from the observations by computing their spatial dependence

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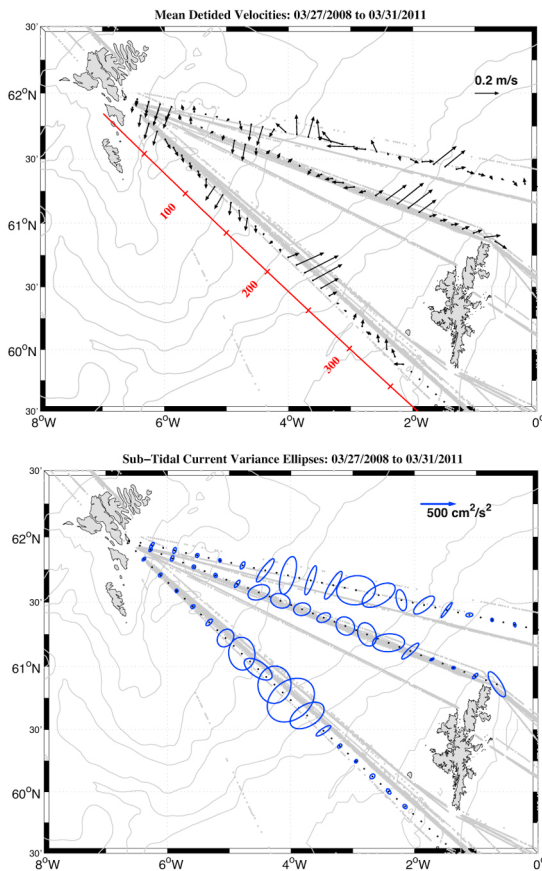


Figure 1. (top) Mean velocity vectors in 10 km steps along the three FSC sections vertically averaged between 20 and 100 m depth. (bottom) Detided variance ellipses in 20 km steps vertically averaged between 20 and 100 m depth. Bathymetry contours at 50, 100, 500, and 1000 m.

in the upper 100 m using a least squared method [Dunn, 2002; Wang *et al.*, 2004], and assuming that those results apply throughout the water column. The method has been shown to work well when there is sufficient data and applying it to the Norröna data has produced amplitudes and tidal ellipse orientations for the M2 component that agree well with Larsen *et al.*'s [2000] mooring observations on the Faroe shelf adjacent to the Shetland-Faroe Channel and with Allen's [1995] moored observations on the edge of the Iceland shelf. In upper 100 m of the FSC area the de-tiding removed about 40 percent of the total velocity variance while it removed about 60 percent over the IFR. So the approach has been to assume that the upper 100 m tidal estimates represent a barotropic surface tide and we have removed that throughout the water column. There remains the problem that the surface tides are not, in fact, vertically uniform, at least north and east of the Faroes as shown by Larsen *et al.* [2008]. Nevertheless, the residual tidal components left after the removal of the upper 100 m contribution are much reduced and we rely on spatial and temporal bin averaging to reduce the tidal "noise" to insignificance. The standard errors for the transports through the sections were reduced by about a factor of two through this de-tiding procedure.

[6] When computing transports, the shallowest measured velocities were extended to the surface, and the deepest bin over the bottom with at least 5 valid measurements was

extended to the bottom, typically an additional 50–75 m over the IFR section. Inspection of the mean velocity structure from three bottom-mounted ADCPs just west of the Faroes on the IFR (courtesy Dr. B. Hansen) indicate that the bottom boundary layer is <15 m thick.

3.1. Results From the Faroe Shetland Channel

[7] Although the M/F Norröna has served Norway and Denmark along three different routes across the FSC, Figure 1, the most heavily sampled route to date goes just south of the Shetlands. A total of 131 ADCP sections between March 2008 and March 2011 have been obtained along this southern route with a combined total of 135 along the two northern sections. All three sections capture the well-known Slope Current that carries warm, salty North Atlantic water through the FSC continuing on as the inner branch of the Norwegian Atlantic Current, Figure 1 (top). We focus here on the most-sampled southern section. The highest measured 3-minute ensemble speed in the Slope Current was 0.96 ms^{-1} . On the Faroese side a well-defined flow follows the bathymetry to the south. The de-tided variance ellipses from the upper 100 m in Figure 1 (bottom) reveal considerable eddy activity across the channel; it is strongest at the offshore (or baroclinic) side of the Slope Current [Sherwin *et al.*, 2008].

[8] Figure 2 (top) reveals the well-known vertical structure of the Slope Current: strong and weak vertical shear on its offshore and onshore sides, respectively [Sherwin *et al.*, 2008]. Most of the rest of the channel shows southward velocities at all depths: weak in the center and strong and slightly bottom-intensified on the Faroese slope. The southward velocities at all depths west of 200 km results in a larger than previously recognized southward transport on the Faroese side of the channel, 2.6 Sv between the shelf break at 100 km and 200 km (surface to $\sigma_\tau = 27.8$), Figure 2 (bottom). The Slope Current between 200 and 250 km sums to 3.7 Sv from the surface to $\sigma_\tau = 27.8$ (400^+ m depth), in close agreement with Østerhus *et al.* [2005, hereinafter ØTJH], and Sherwin *et al.* [2008]. An additional 0.3 Sv flows north on the Shetland shelf for a total of 4.1 Sv. The net transport through the channel between the surface and the $\sigma_\tau < 27.8$ surface is 0.9 Sv to the north.

3.2. Results From the Iceland-Faroe Ridge

[9] Unlike the FSC, the IFR section lies fully exposed to the North Atlantic and the Norwegian Sea resulting in higher sea state and swell conditions much of time. This restricts good data collection to the summer months June–July–August for a total of 99 sections used here. The mean flow vectors, Figure 3 (top), show clearly that the inflow into the Nordic Seas takes place over the southeastern half of the section. The set of nearly along-track vectors between 12° and 10° W correspond to the Iceland-Faroe Front flowing southeast along the IFR before it turns east between 63° and 64° N. The de-tided variance ellipses from the upper 100 m (Figure 3, bottom) indicate a rather uniform distribution of eddy kinetic energy all along the section. The striking variation in their orientation remains to be investigated, but we conjecture that the shape of the bathymetry may be an important factor. The vertical structure of the mean flow normal to the ship track (Figure 4, top) shows the principal inflow at 300 km to be significantly baroclinic: strongest at/near the surface, weaker at depth. Unexpectedly,

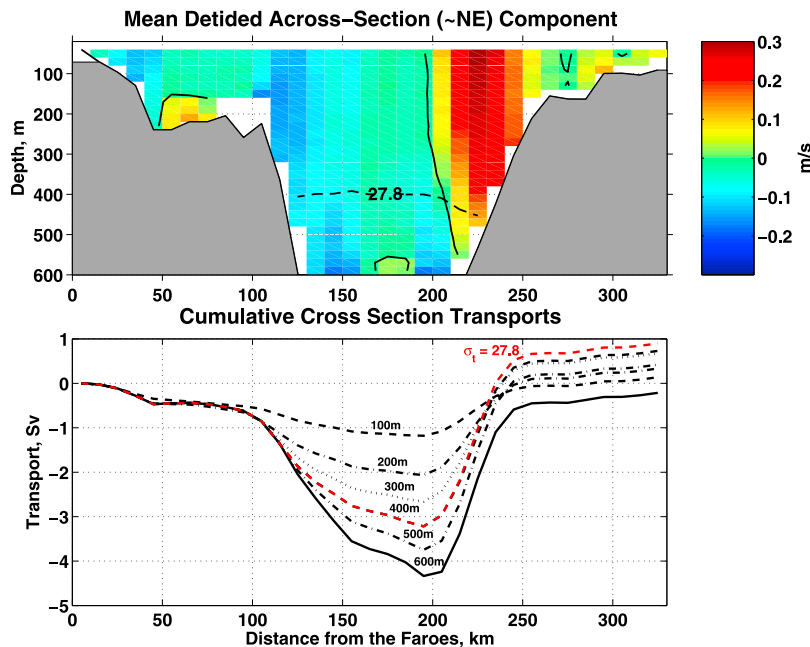


Figure 2. (top) Vertical structure of cross-track velocity along the southern FSC route between the Faroes and the southern tip of the Shetlands. Red colors to the north, blue colors to the south. The heavy black line indicates zero velocity. (bottom) Cumulative, vertically integrated transport from the surface to various depths along the southern line from the Faroes towards Shetland. The 100 m transports include the upper ~ 20 m missed by the ADCP by extending the shallowest velocities to the surface. In a similar manner the red line indicates the cumulative transports from the surface to the $\sigma_t = 27.8$ surface (~ 400 m depth).

the zero-velocity demarcation between in- and outflow is almost depth independent. Nonetheless, the inflow is strongest towards the surface at the southeastern end and outflow is strongest (broadest) at depth at the northwestern end. This pattern also shows up in the transport integrals (Figure 4, bottom), which shows a -1.5 Sv outflow from the Iceland shelf break (at 90 km) to 230 km with much of the shear (increase in outflow with depth) located between 200 m and the bottom. The top-to-bottom 5.9 Sv inflow between 230 km and the Faroes is larger than expected, but it includes water circulating around the Faroes (discussed below). The top 100 m shows no net outflow in the northwest and 1.9 Sv inflow in the southeast. Integrating down to 200 m results in a -0.4 Sv outflow in the western half and $+3.6$ Sv inflow east of 230 km.

4. Volume, Heat and Salt Fluxes

[10] This study differs from earlier studies of fluxes across the Iceland-Faroe-Scotland ridge in that it measures velocity directly without the aid of any hydrographic information. While this is a significant step forward in terms of quantifying volume fluxes, the lack of hydrography means we cannot identify water type, and hence we cannot directly measure either heat or salt flux, both of relevance to an improved understanding of the ocean's role in climate. In an attempt to estimate these, we have extracted from the ICES hydrographic database all hydrographic data since January 1, 1950. The stations in the FSC are distributed throughout the year with peaks in May/June and September/October. For the IFR the stations are more tightly clustered in early summer. We use ODV (R. Schlitzer, Ocean Data View,

2011, available at <http://odv.awi.de>) to preview and select the area and time of interest. From this subset we construct mean profiles of T and S every 10 km along the two sections where each profile uses with equal weight all hydrographic data within 25 km radius. Figure 5 shows the resulting mean T and S fields for the FSC, and Figure 6 shows the corresponding fields for the IFR. Integrating the product of mean velocity (Figures 2, top and 4, top) with these fields gives us the flux of heat, relative to 0°C , and salt through the sections (Table 1).

[11] The FSC flux is given in two parts: a directly measured upper layer flux to the $\sigma_t = 27.8$ surface, using the observed velocity profile and in the case of heat and salt, the mean temperatures and salinities from Figure 5 (line 1). The lower layer flux from Hansen and Østerhus [2007] is -1.9 ± 0.3 Sv with an average temperature = 0.25°C and salinity = 34.93 PSU (line 2). IFR fluxes appear in line 3, and the sum of both sections appears in line 4. The uncertainty in the upper layer net flow in the FSC and IFR is about ± 0.1 and ± 0.25 Sv, respectively. The RMS uncertainty of the two is ± 0.27 Sv; we round this to ± 0.3 Sv. (It is assumed that the 0.25 Sv standard error of the IFR inflow is the dominant uncertainty in the subsequent budget calculations.)

5. Discussion

[12] Temporal coverage of currents in the FSC spans almost the entire year, but is more complete during the summer half-year when weather is better. The data used here span three years with most from 2009 and 2010 as the Norröna switched operation to the middle line (see Figure 1)

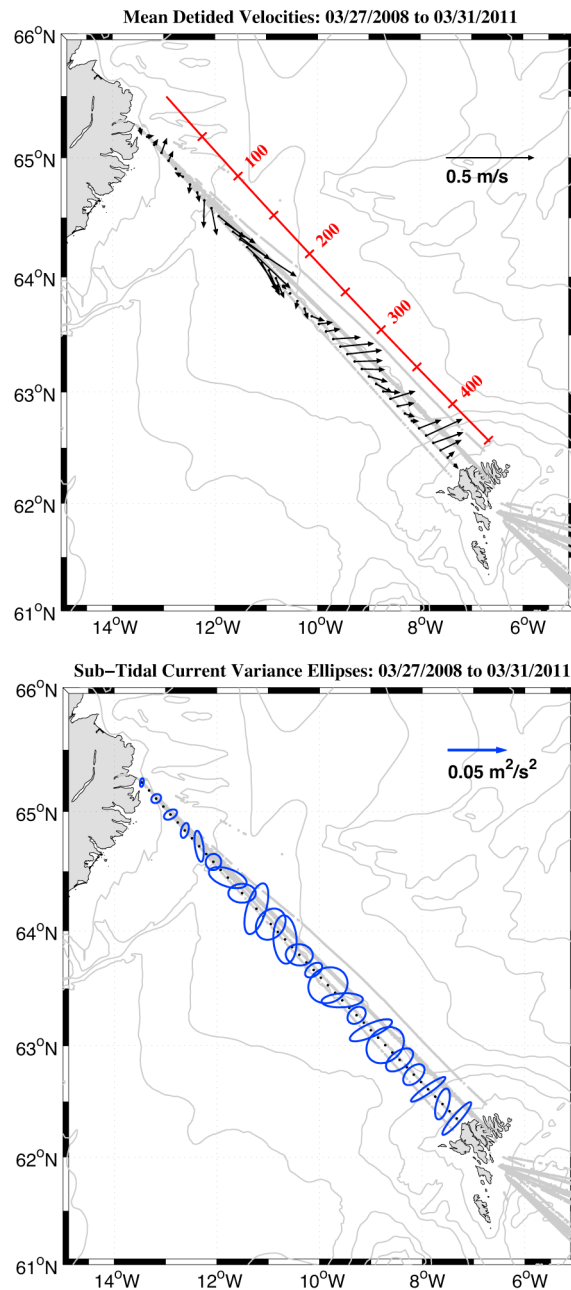


Figure 3. (top) Mean velocity vectors in 10 km steps along the IFR section vertically averaged between 20 and 100 m depth. (bottom) Detided variance ellipses in 20 km steps vertically averaged between 20 and 100 m depth. Bathymetry contours at 50, 100, 500, and 1000 m.

in early 2011. According to *Sherwin et al.* [2008] the Slope Current has a minimum in spring and a maximum in fall so even though our data are weighted towards the summer half-year, they span the spring-fall transition and therefore should give a reasonable annual estimate. As the program continues it will be possible to examine the annual and longer time scales in greater detail. Data collection in the IFR region is unfortunately limited to the summer months June, July and August due to the bubble sweep-down problem. For the purposes of this study the IFR data will be

used as if they were annual averages. The justification for this comes from the *Hansen et al.* [2003] study, which notes little seasonal variation in the Faroe Current. Little is known about the variability of the southward flow east of Iceland, leaving us little choice at present but to treat the measured mean velocity field as if it were an annual average.

[13] These first results from the Norröna ADCP operation corroborate previous estimates of inflow of North Atlantic water on the eastern sides of both the FSC and the IFR. The 3.7 Sv inflow along the Shetland slope matches closely earlier estimates, and the 3.9 Sv over the deeper part of the IFR corresponds to the 3.7 Sv Faroe Current. This study also identifies a well-defined -1.6 volume transport south along the upper slope east of the Faroes, and a 1.5 Sv flow tightly locked to the Faroe slope in the IFR section. Very likely this is a tidally-driven circum-Faroe boundary current [*Larsen et al.*, 2008]. It would account for 1/2 the 3.2 Sv southward transport in the FSC above the $\sigma_\tau = 27.8$ surface. The excess, 1.6 Sv, we suggest, joins the north-flowing Slope Current. The addition of re-circulated water to the Slope Current can be seen in the fact that the mean flow north in the Slope Current (Figure 2, top) is wider than that of the high salinity wedge (Figure 5, bottom).

[14] To estimate the total inflow into the Nordic Seas, we add the 0.75 Sv flow north along the west coast of Iceland [*Jónsson and Valdimarsson*, 2005] to our 10.1 Sv through the FSC and IFR to obtain 10.9 ± 0.3 Sv. The total outflow in Table 1 sums to 6.5 Sv. Of course, both in- and outflows include the ~ 1.6 Sv circulating around the Faroes, so a more useful statement might be that $10.9 - 1.6 = 9.3$ Sv enters the Nordic Seas. This is the volume that loses its heat to the atmosphere and leaves the surface as it courses its way north and subsequently back south towards the Greenland-Scotland ridge.

[15] This $9.3 \text{ Sv} \pm 0.3 \text{ Sv}$ inflow must exit the Nordic Seas back into the North Atlantic since the only other exits, the Bering Strait and Canadian Archipelago, are too shallow. We estimate that $6.5 - 1.6$ (recirculating water) = 4.9 Sv exits through the FSC and IFR leaving $9.3 - 4.9 = 4.4 \pm 0.3$ Sv, which must exit through the Denmark Strait (DS). This estimate is comparable to but somewhat larger than the findings of earlier studies: i) *Girton et al.* [2001] obtain from 7 sections taken over a week an average outflow of 2.7 ± 0.6 Sv ($\sigma_\theta > 27.8$), ii) *Macrandar et al.* [2005] report a 3.6 to 3.1 Sv decrease (annual averages) over a three year period, and iii) *Dickson et al.* [2008] estimate about 4.0 ± 0.4 Sv overflow ($\sigma_\theta > 27.85$). Since our transport estimate is larger, it is quite possible that some of it flows south as less dense water than considered in the above studies, making for potentially even better agreement.

[16] The net heat flux to the Nordic Seas through the FSC and the IFR, based on a mean temperature distribution advected by a mean flow north sums to 176 TW. The total net heat supply available the Nordic Seas thus becomes about 176 TW plus 22 TW west of Iceland [*Jónsson and Valdimarsson*, 2005], less 27 TW outflow through DS (4 Sv @ 1.7°C [*Dickson et al.*, 2008, Table 19.2]), totaling 171 TW northward. The uncertainty of this number due to the 0.3 Sv uncertainty in inflow is probably at the 10% level. This result can be compared with the findings of a recent study by *Segtnan et al.* [2011], who estimate the total heat loss to the atmosphere in the Nordic Seas to be 198 TW.

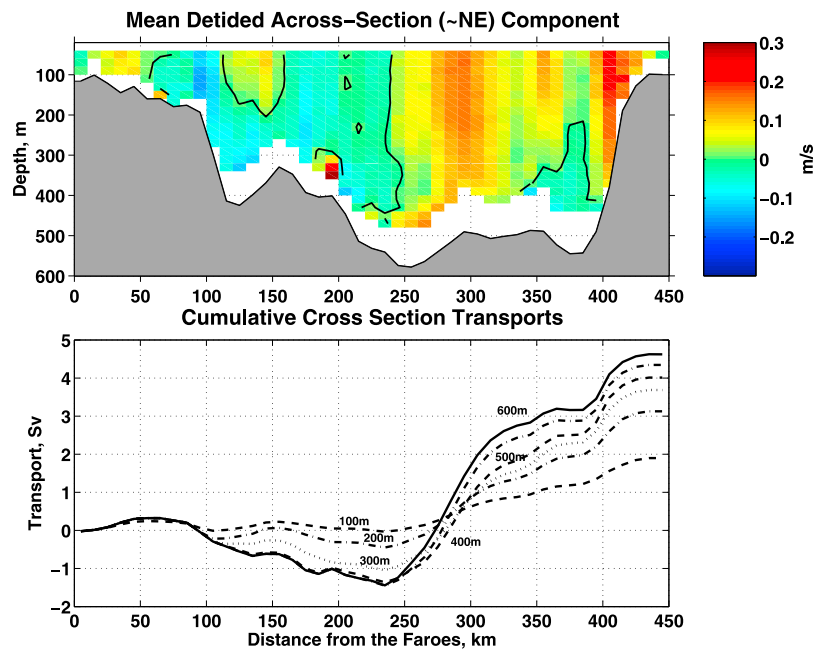


Figure 4. (top) Vertical structure of cross-track velocity along the IFR line between Iceland and the Faroes. Red colors to the north, blue colors to the south. The heavy black line indicates zero velocity. (bottom) Cumulative vertically integrated transport from the surface to various depths along the line from Iceland to the Faroes.

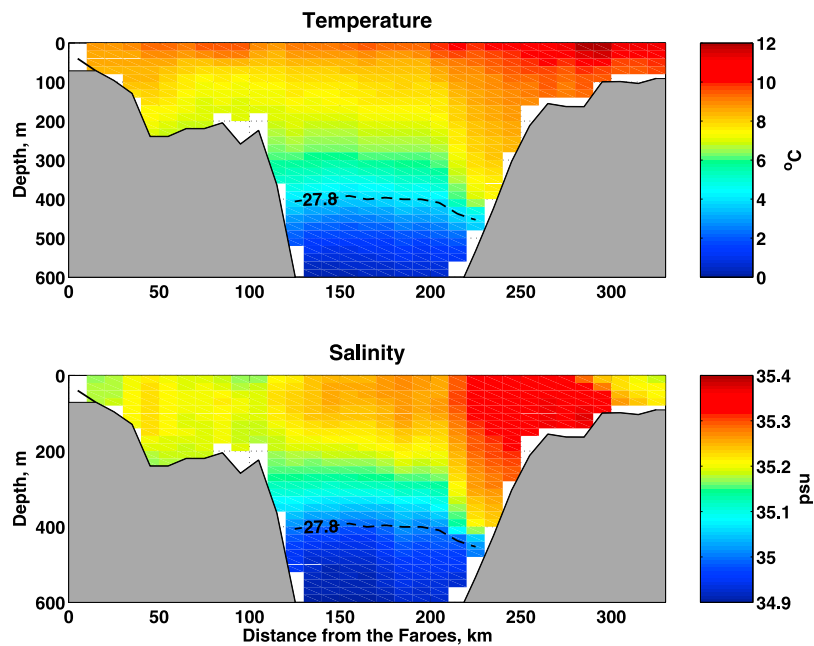


Figure 5. Mean (top) temperature and (bottom) salinity field along the southern FSC line. Colorbars indicate temperature in °C and salinity in PSU, respectively. The $\sigma_t = 27.8$ line in the two panels separates volume, heat and salt fluxes estimated directly (from the surface to this line) and estimates from Hansen and Østerhus [2007] (all deeper waters).

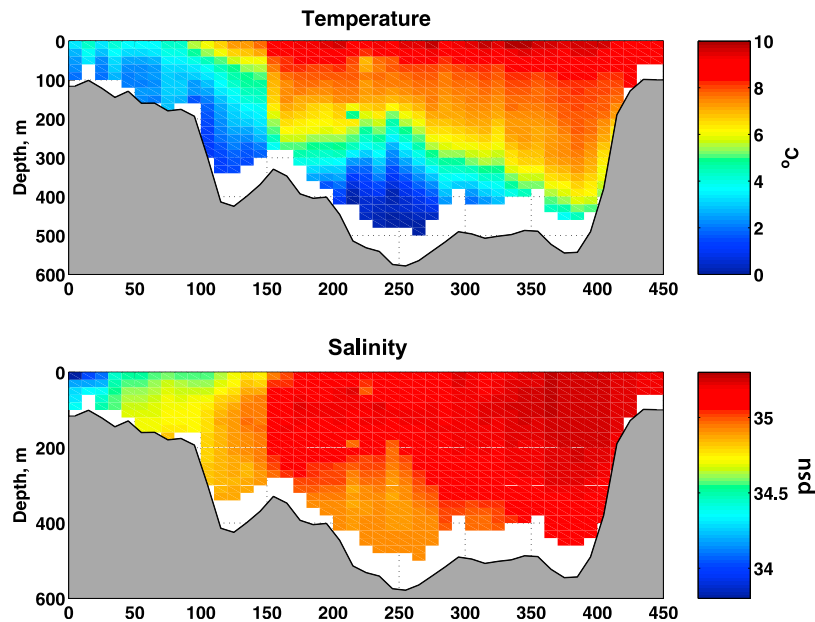


Figure 6. Mean (top) temperature and (bottom) salinity field along the IFR section. Colorbars indicate temperature in °C and salinity in PSU, respectively.

[17] To obtain the total inflow of salt into the Nordic Seas we include the transport northwest of Iceland [Jónsson and Valdimarsson, 2005]. They do not report salt flux per se, but a rough estimate might be their 0.75 Sv volume flux times a mean salinity of $35.05 \text{ PSU} = 0.26 \times 10^8 \text{ kgs}^{-1}$. Add this to our net transport through the FSC and IFR of 1.19×10^8 for a total of $1.45 \times 10^8 \text{ kgs}^{-1}$, all of which must return south through DS assuming steady state conditions. We note that Dickson *et al.* [2008] estimate a salt transport of $1.4 \times 10^8 \text{ kgs}^{-1}$ for waters denser than 27.85 . The mean salinity of the overflow water would therefore be $1.45 \times 10^8 / 4.4 \text{ Sv} = 33.0 \text{ PSU}$ compared to an observed 34.88 PSU . The closeness of the agreement indicates a measure of internal agreement to the flux estimates. But as with the heat fluxes, more can be done to accurately determine heat and salt transports through the Nordic Seas. Since profiling salinity with XCTDs is not affordable at present, a good start will be concurrent XBT/ADCP sections together with updated T/S information for both inflows. Surface salinity data from the onboard FerryBox system will help too. The Norröna operation is ongoing and plans are being made to include XBT operations starting in 2012. This will allow us to better measure heat flux and partition it into its mean and eddy components across the seasons.

Table 1. Summary of FSC and IFR Fluxes^a

	Volume Flux (Sv)			Heat Flux (TW)			Salt Flux ($\text{kg s}^{-1} \times 10^8$)		
	Net	North	South	Net	North	South	Net	North	South
FSC	0.9	4.1	-3.2	44.2	132.5	-88.3	0.31	1.39	-1.08
$\sigma_\tau < 27.8$									
FSC	-1.9	0	-1.9	-1.9	0	-1.9	-0.66	0	-0.66
$\sigma_\tau > 27.8$									
IFR	4.6	6.0	-1.4	133.6	154.1	-20.5	1.54	1.95	-0.41
Sum	3.6	10.1	-6.5	176	287	-111	1.19	3.34	-2.15

^aThe three sub-columns represent net, north, and south transports, respectively.

[18] **Acknowledgments.** The authors wish to extend their sincerest thanks to Jógvan í Dávastovu of the Smyril Line. We are most grateful for his and Smyril Line's support and encouragement for this project. We thank S. Anderson-Fontana for her excellent support and processing of the ADCP data and George Schwartz for his assistance in installing the ADCP system on the M/F Norröna. We thank the National Science Foundation for its support of this project through grants 04552274 and 1060752 to Stony Brook University and grants 0452970 and 1061185 to the University of Rhode Island. We also thank the two reviewers for their excellent comments and suggestions; they have led to a much-improved paper.

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