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The decomposition of the Faroe-Shetland Channel water masses using Parametric Optimum Multi-Parameter analysis

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ABSTRACT

The Faroe-Shetland Channel (FSC) is an important conduit for the poleward flow of Atlantic water towards the Nordic Seas and, as such, it plays an integral part in the Atlantic's thermohaline circulation. Mixing processes in the FSC are thought to result in an exchange of properties between the channel's inflow and outflow, with wider implications for this circulation; the nature of this mixing in the FSC is, however, uncertain. To constrain this uncertainty, we used a novel empirical method known as Parametric Optimum Multi-Parameter (POMP) analysis to objectively quantify the distribution of water masses in the channel in May 2013. This was achieved by using a combination of temperature and salinity measurements, as well as recently available nutrient and $\delta^{18}O$ measurements. The outcomes of POMP analysis are in good agreement with established literature and demonstrate the benefits of representing all five water masses in the FSC. In particular, our results show the recirculation of Modified North Atlantic Water in the surface layers, and the pathways of Norwegian Sea Arctic Intermediate Water and Norwegian Sea Deep Water from north to south for the first time. In a final step, we apply the mixing fractions from POMP analysis to decompose the volume transport through the FSC by water mass. Despite a number of caveats, our study suggests that improved estimates of the volume transport of Atlantic inflow towards the Arctic and, thus, the associated poleward fluxes of salt and heat are possible. A new prospect to more accurately monitor the strength of the FSC branch of the thermohaline circulation emerges from this study.

1. Introduction

The poleward flow of warm and saline Atlantic water through the Faroe-Shetland Channel (FSC) accounts for a large fraction of the total Atlantic inflow into the Nordic Seas (~2.7 Sv; Berx et al., 2013). This is slightly less than the inflow over the Iceland-Faroe Ridge (~3.8 Sv), and significantly greater than that through the Denmark Strait (~0.8 Sv) (Østerhus et al., 2005). As such, the FSC is an important conduit for the poleward transport of salt, heat and nutrients, which, for example, creates favourable conditions for the economically important fish stocks in the Nordic Seas (Larsen et al., 2012). Furthermore, this transport of salt also enhances intermediate and deep water formation in the Arctic (Hansen et al., 2003). These intermediate and deep waters then flow back towards the south via the same pathways, transporting a total ~5.6 Sv of water into the North Atlantic (Sherwin et al., 2008a), of which ~2.2 Sv overflows through the FSC (Hansen and Østerhus, 2007; Sherwin et al., 2008a). The FSC is therefore an integral gateway to the present operation of the global thermohaline circulation and, as such, research into the nature of mixing and circulation within the channel is important.

Monitoring of the properties (temperature and salinity) of oceanic water masses in the FSC started in the early 20th century (Dickson, 1903). However, a programme of regularly repeated surveys was only established from the 1970s. From 2000, the analysis of samples for nutrient concentrations was added. These observations have focussed on two hydrographic sections across the FSC: the Nolso-Flugga (NOL) and Fair Isle-Munken (FIM) sections (Fig. 1). Through these measurements, it is now well-established that five water masses of contrasting origin flow through the FSC, as summarised by Hansen and Østerhus (2000): North Atlantic Water (NAW), Modified North Atlantic Water (MNAW), Modified East Icelandic Water (MEIW), Norwegian Sea Arctic Intermediate Water (NSAIW) and Norwegian Sea Deep Water (NSDW). These water masses are distinguished by distinct temperature and salinity characteristics (Table 1), which have been used to trace their presence or absence in the channel (Martin, 1993; Turrell et al., 1999; Borenäs et al., 2001).

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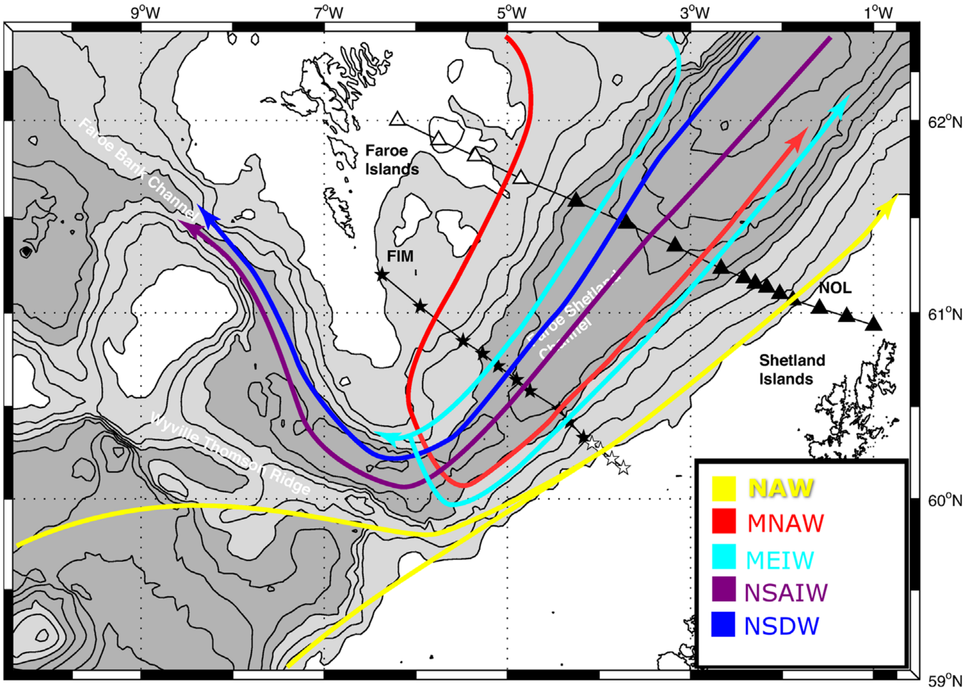

Fig. 1. Map of the Faroe-Shetland Channel showing two standard hydrographic sections: Nolso-Flugga (NOL; triangles), and Fair Isle-Munken (FIM; stars). General circulation of the 5 main water masses is also shown (NAW = North Atlantic Water; MNAW = Modified North Atlantic Water; MEIW = Modified East Icelandic Water; NSAIW = Norwegian Sea Arctic Intermediate Water; NSDW = Norwegian Sea Deep Water). Open symbols show where SWT definitions were determined for MNAW and NAW (see text).

Table 1
Source Water Types (SWTs) for each water mass used in the POMP analysis (no brackets). In brackets, reference SWT ranges taken from literature and databases for comparison. In the bottom row, uncertainties in each hydrographic property used for the weighting. Phosphate, nitrate and silicate reference SWT ranges for the MEIW, NSAIW and NSDW (except for the NSDW phosphate range) were estimated from data obtained from the northern boundary of the FSC to minimise the influence of mixing. δ^{18}O reference SWT ranges for the NAW were estimated from data obtained from the Rockall Trough; from the Iceland Basin and areas southwest of the Rockall Trough for the MNAW; from around the northern coast of Iceland for the MEIW; from the Lofoten and Norwegian Basins for the NSAIW; and from the Eurasian and Greenland Basins for the NSDW.

	Potential temp. (°C)	Salinity	Phosphate (μmol/l)	Nitrate (μmol/l)	Silicate (μmol/l)	δ^{18}O (‰)
NAW	10.15 (9.5–10.5)[a]	35.42 (35.35–35.45)[a]	0.65 (0.6–1.1)[c]	10.21 (9–16)[c]	3.18 (2.5–7.5)[c]	0.49 (0.38–0.5)[f]
MNAW	8.17 (7–8.5)[a]	35.27 (35.1–35.3)[a]	0.77 (0.6–1.1)[c]	12.41 (9–16)[c]	4.84 (2.5–7.5)[c]	0.42 (0.19–0.42)[f]
MEIW	2.63 (2–4.5)[b]	34.89 (34.76–34.99)[b]	0.88 (0.85–0.97)[d]	13.2 (12.1–13.2)[d]	6.29 (5.8–7.3)[d]	0.24 (0.07–0.29)[f]
NSAIW	−0.17 (−0.5–0.5)[a,b]	34.90 (34.89–34.91)[b]	0.96 (0.9–1.1)[d]	14.11 (13.2–14.9)[d]	7.60 (9.6–12.3)[d]	0.30 (0.14–0.42)[f]
NSDW	−0.79 (< −0.5)[a]	34.91 (=34.91)[a]	1.02 (0.8–1.1)[d]	15.00 (9.6–14.8)[d]	11.77 (=11.5)[e]	0.26 (0.13–0.40)[f]
Uncertainty	0.5	0.024	0.12	1.95	1.16	0.12

[a] Hansen and Østerhus (2000);
[b] Borenäs et al. (2001);
[c] Johnson et al. (2013);
[d] World Ocean Atlas 2013 (Garcia et al. 2014);
[e] van Bennekom (1985);
[f] Global Seawater Oxygen-18 Database (version 1.21) (Schmidt et al., 1999).

While temperature–salinity (T–S) plots have been useful for identifying both spatial and temporal variability in the water masses, they cannot always explain its cause. For instance, MEIW is identified in T–S space by a convex curve shape. Seasonal variations in the degree of curve convexity have, thus, implied that the MEIW is only seasonally present in the FSC (Borenäs et al., 2001). However, while an absence of convexity may imply an absence of MEIW, it may equally imply intense mixing, or a change in MEIW's source water properties. Similarly, while it is thought that MNAW and MEIW partially recirculate between NOL and FIM (Dooley and Meincke, 1981; van Aken, 1988; Sherwin et al., 1999, 2008b), it is not known exactly how much recirculation occurs, because recirculation affects T–S curve shape in a similar manner to mixing. As such, mixing relationships between the FSC water masses are currently uncertain. An improved understanding of the mixing relationships is necessary, however, to fully characterize the exchange of heat, salt and nutrients between the FSC inflow and overflow. The nature of this mixing determines whether there is a potential for long term trends in the properties of one water mass to propagate into another, with wider implications for the thermohaline circulation (Hosegood et al., 2005). Indeed, mixing in the FSC between freshening Atlantic waters and intermediate waters may have enhanced wide-scale freshening of the northern North Atlantic in the 1960s, 70s and 80s, which is thought to have weakened convective overturning (Dickson et al., 1988). As global climate models have simulated a future weakening of the thermohaline circulation in response to greenhouse gas forcing (Gregory et al., 2005), it is thus vital that we understand how mixing in the FSC might act as a positive feedback mechanism in this globally significant process.

Potential mixing relationships have been identified in the FSC through the examination of mixing mechanisms (Hosegood and van Haren, 2004; Sherwin et al., 2006; Hall et al., 2011), but this can only yield qualitative results and does not quantify the mixing that occurs. However, a number of empirical "black box" mixing models do exist, and these can be used to objectively calculate mixing fractions (the percentage of each water mass at each point in the channel) with relative ease. The simplest of these, the three-point mixing model (Hermann, 1967), has already been successfully applied to the FSC (Turrell et al., 1999; Hansen et al., 2003;