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Transport estimates of the Western Branch of the Norwegian Atlantic Current from glider surveys

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ABSTRACT

The northernmost limb of the Atlantic Meridional Overturning Circulation (AMOC), so relevant for understanding decadal climate variability, enters the Nordic Seas as the Norwegian Atlantic Current and continues on to recirculate in the Arctic Ocean. The strength of the Eastern Branch of the Norwegian Atlantic Current has been systematically monitored for over 15 years at the Svinøy section off southern Norway, whereas the strength of the Western Branch has not. We therefore used autonomous gliders to monitor and quantify the strength of this broader branch at the Svinøy section, located 500 km downstream from the Iceland–Scotland Ridge, and at the Station Mike section 300 km further downstream. The gliders' diving depth is 1000 m, spanning the warm Atlantic Water. The current encompasses more than warm Atlantic Water; we find that the transport peaks in two distinct temperature ranges, one around 7.5–8 °C (Atlantic Water, carrying 7 Sv (1×10^6 m^3/s)) and another around −0.5 °C (Norwegian Sea Deep Water, carrying 12 Sv). Contrary to earlier expectations, our results indicate that the Western Branch carries as much water of Atlantic origin (temperature > 7.5 °C) as the Eastern Branch. It should therefore be included in future monitoring plans for this region.

1. Introduction

The Norwegian Atlantic Current (NwAC) is the northern limb of the Gulf Stream system and carries warm and saline water of Atlantic origin from the North Atlantic through the Nordic Seas to the Arctic Ocean. Quantifying and understanding its variability is important for our understanding of the regional climate system in northern Europe and Eurasian Arctic.

The NwAC enters the Nordic Seas primarily across the Iceland–Faroe Ridge and through the Faroe–Shetland Channel (Fig. 1). The current continues as a two-branch system through the Nordic Seas (Poulain et al., 1996; Orvik and Niiler, 2002). The Western Branch of the Norwegian Atlantic Current can be considered an extension of the Iceland–Faroe Frontal Jet which continues eastward as the Faroe Current north of the Faroe Islands. The Faroe Current has been monitored since 1997. The estimated average volume transport of water warmer than 5 °C for 1997–2001 is 3.8 Sv ($1\ Sv=10^6\ m^3\ s^{-1}$), with a peak in the temperature range 7–7.5 °C (Hansen et al., 2003).

Current meter measurements of the Eastern Branch in the Faroe–Shetland Channel between 1994 and 2008 yield an average transport of 3.8 Sv (Østerhus et al., 2005), all warmer than 8 °C (Mauritzen et al., 2011). A recent estimate of the net northward transport between Shetland and Iceland, based on direct, repeat, ship-of-opportunity current measurements, supports the earlier measurements by finding that there is a net northward flow across the section of 8.5 Sv (Rossby and Flagg, 2012).

The Eastern Branch represents a quasi-barotropic current along the Norwegian shelf edge toward the Fram Strait, with its core over the 500 m isobaths. The Western Branch, on the other hand, is a baroclinic frontal jet further offshore, continuing through the Nordic Seas toward the Fram Strait (Orvik and Niiler, 2002). There is extensive exchange of water between the two branches (Rossby et al., 2009), such that also the area between the branches is filled with warm and salty Atlantic water (Fig. 1). Parts of the Iceland–Faroe inflow actually join the Eastern Branch already in the Faroe–Shetland Channel (Poulain et al., 1996).

Within the Nordic Seas, the warm Atlantic Water encounters colder and fresher water masses on all sides (Fig. 1). Despite large

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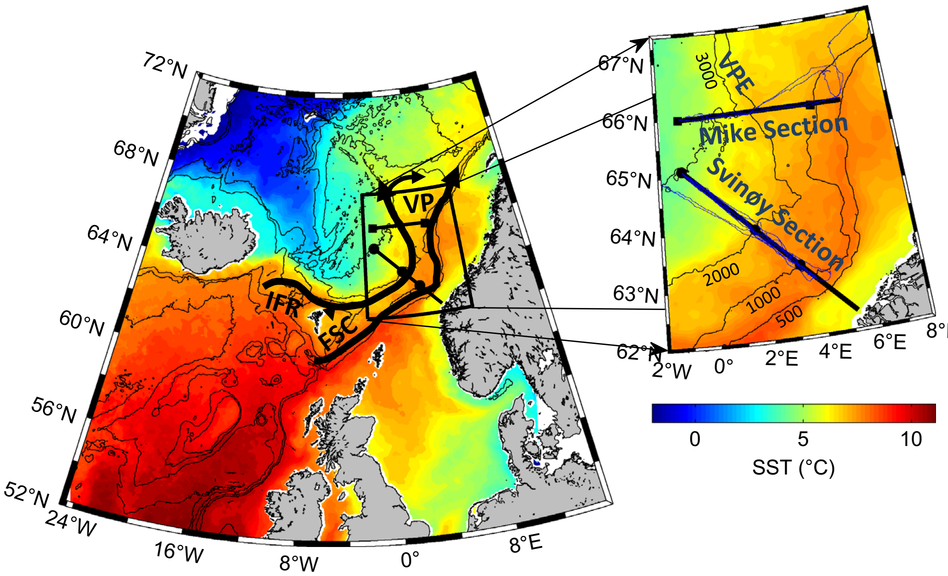

Fig. 1. The NwAC in the southern part of the Nordic Seas is visible in the mean SST during January–March 2009 (satellite data courtesy Steinar Eastwood, Norwegian Meteorological Institute; Copyright (2009) EUMETSAT). The Svinøy section (extended northwestward to 1°W, 65.1°N) is shown, together with dots denoting the locations of (from northwest to southeast along the section) the Seaglider offshore target (at ~3000 m bottom depth), the 2000 m isobath, and the 1100 m isobaths (used as an inshore limit of the Western Branch, see text). The following isobaths are shown: 500 m, 1000 m, 2000 m, and 3000 m. The zonal Station Mike section at 66°N extended from the Norwegian continental shelf, past the former Ocean Weather Station Mike to 1°W (marked with a square). The 1100 m isobath is also marked with a square. The two branches of the Norwegian Atlantic Current are sketched into the figure. The small map zooming in on our area shows the Seaglider trajectories at the Svinøy and Station Mike sections. Key bathymetric features are labeled with acronyms: IFR—The Iceland–Faroe Ridge; FSC—The Faroe–Shetland Channel; VP—The Vøring Plateau, and VPE—The Vøring Plateau Escarpment.

temporal variability in temperature and salinity within the key water masses in this region during the 20th century (Dickson and Østerhus, 2007), a temperature–salinity diagram reveals a well-defined transition between the warm and saline waters of Atlantic origin and the colder and fresher surrounding water masses in the vicinity of $S = 35$ (Fig. 2). Therefore there exists a strong tradition, stemming from Helland-Hansen and Nansen's seminal work “The Norwegian Sea” (1909), to define Atlantic Water in the Norwegian Sea as water with salinities higher than 35 (Fig. 2), corresponding to temperatures higher than 4–5 °C in the southern Nordic Seas and colder further north. On the eastern side, the shallow Norwegian Coastal Current runs northward along the coast of Norway from the Baltic, picking up river runoff along the way (Mork, 1981). Its salinity is typically less than 34.8, and in the winter its temperature is in the 2–5 °C range (Saetre and Ljoen, 1972). On the western side, colder waters of Arctic origin enter the Nordic Seas in the western Fram Strait as Polar Water with salinities lower than 34.5 and temperatures around 0 °C. All these water masses are found in the upper ocean, and there are broad regions of the upper Nordic Seas that consist of mixtures of these water masses. The deep waters of the Nordic Seas originate in the Greenland Sea and in the Arctic Ocean. Salinities are typically around 34.9 and temperatures less than 0 °C (Aagaard et al., 1985) (Fig. 2).

The standard “Svinøy section” (Fig. 1) captures the Norwegian Atlantic Current about 500 km downstream from the Iceland–Scotland Ridge. The temperature and salinity of this section has been observed several times a year for more than 50 years, as part of the Norwegian Institute of Marine Research's standard hydrographic monitoring program (www.imr.no; see also Mork and Blindheim, 2000). In addition, the current strength of the Eastern Branch of the NwAC has been monitored continuously since 1995 with moored current meters. The average transport estimate for water warmer than 5 °C is 4.4 Sv and the transport peaks in the temperature range 8.5–9 °C (Orvik et al., 2001; Orvik and Skagseth, 2005; Mauritzen et al., 2011). The temperature range of the Eastern Branch at the Svinøy section is within the temperature

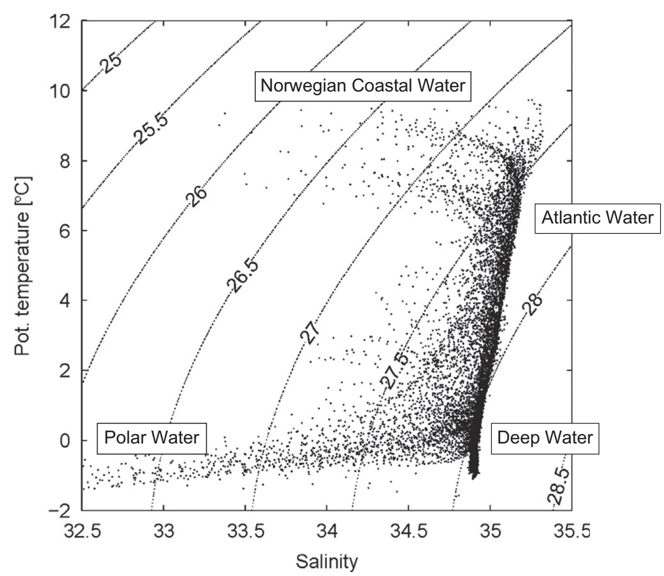

Fig. 2. Potential Temperature–Salinity diagram, showing the main water masses of the Nordic Seas. Based on the World Ocean Atlas 2005 (Antonov et al., 2006; Locarnini et al., 2006). Also shown are lines of constant σ_θ [kg/m^3].

range of the two inflow branches at the Iceland–Scotland Ridge, but with about half of the total warm water volume transport at the ridge. Achievements of accurate estimates of the AI to the Nordic Seas have been addressed in a series of papers over the past decades using different methodologies as budget considerations (e.g. Mauritzen (1996); Worthington, 1970) and direct measurements over the ISR (Hansen and Østerhus, 2000) and in the Svinøy section just to the north of the FSC (Mork and Blindheim, 2000; Orvik et al., 2001); converging toward an overall estimate of about 8 Sv.

Transport estimates of the Western Branch at the Svinøy section are sparse, and mainly based on dynamic calculations