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Observed and modeled pathways of the Iceland Scotland Overflow Water in the eastern North Atlantic

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ABSTRACT

The spreading of Iceland Scotland Overflow Water (ISOW) in the eastern North Atlantic has largely been studied in an Eulerian frame using numerical models or with observations limited to a few locations. No study to date has provided a comprehensive description of the ISOW spreading pathways from both Eulerian and Lagrangian perspectives. In this paper, we use a combination of previously unreported current meter data, hydrographic data, RAFOS float data, and a high resolution (1/12°) numerical ocean model to study the spreading pathways of ISOW from both of these perspectives. We identify three ISOW transport cores in the central Iceland Basin (~59°N), with the major core along the eastern boundary of the Reykjanes Ridge (RR) and the other two in the basin interior. Based on trajectories of observed and/or numerical floats seeded along 59°N, we also describe the ISOW spreading pathways and quantify their relative importance. Within 10 years, 7–11% of ISOW from 59°N escapes into the Irminger Sea via gaps in the RR north of the Charlie Gibbs Fracture Zone (CGFZ); the water that moves through these gaps principally originates from the shallower ISOW layer along the RR eastern boundary. 10–13% travels further southward until the CGFZ, where it crosses westward into the western subpolar gyre. 18–21% of ISOW spreads southward along the eastern flank of the Mid-Atlantic Ridge into the Western European Basin (WEB). Most of the remaining water stays in the Iceland Basin over the 10-year period. A model-based investigation provides a first look at the temporal variability of these ISOW pathways. We find that the fraction of southward water exported into the WEB is anti-correlated with the export through the CGFZ, a result assumed to reflect these pathways' interactions with the North Atlantic Current in magnitude and/or position shift.

1. Introduction

Iceland Scotland Overflow Water (ISOW), one of the major components of the lower limb of the Atlantic Meridional Overturning Circulation (AMOC), is formed in the Nordic Seas from these identified sources: open-ocean convection in the Greenland Sea, dense water formation along the Arctic shelves and the transformation of Atlantic water (Rudels et al., 1999; Eldevik et al., 2009). After formation, ISOW flows to the eastern subpolar gyre mainly through the Faroe-Shetland Channel, with a small portion over the Iceland-Faroe Ridge. ISOW entrains the ambient water as it spreads southward primarily along the slope of the northwest Iceland Basin and then out into the eastern North Atlantic (Fleischmann et al., 2001; van Aken and de Boer, 1995).

An understanding of the distribution and variability of ISOW spreading pathways, together with the other two components of the lower limb of the AMOC, the Labrador Sea Water (LSW) and Denmark Strait Overflow Water (DSOW), is fundamental to our understanding of AMOC structure and variability.

Traditionally, the Deep Western Boundary Current (DWBC) was considered the major conduit from the subpolar to the subtropical gyre for these deep water masses. As a consequence of this assumption, DWBC transport variability was roughly equated to variability of the deep AMOC limb (Molinari et al., 1998; Curry et al., 1998; Schott et al., 2006). However, recent studies have demonstrated the importance of interior pathways in exporting LSW (Bower et al., 2009; Lavender et al., 2005; Gary et al., 2012) and the overflow waters (Xu et al., 2015; Lozier et al., 2013; Gary et al., 2011; Stramma et al., 2004) to the subtropical gyre in the western North Atlantic, thus calling into question the DWBC as the sole conduit of deep water masses in the North Atlantic. Besides an interior pathway for overflow waters in the western North Atlantic, studies based on models and Lagrangian floats have identified a southward interior pathway of ISOW along the eastern flank of the Mid-

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Atlantic Ridge (MAR) (Xu et al., 2010; Machín et al., 2006; Lankhorst and Zenk, 2006).

In addition to the southward branch along the eastern flank of the MAR, two other ISOW spreading pathways have also been identified in the eastern North Atlantic: one via gaps in the Reykjanes Ridge (RR) north of the Charlie Gibbs Fracture Zone (CGFZ), and the other via a westward crossing through the CGFZ. The former branch has been mostly studied with models (Xu et al., 2010; Chang et al., 2009), while the latter branch has been studied using both model output (Xu et al., 2010; Chang et al., 2009) and current meter measurements (Saunders, 1994; Bower and Furey, 2017). In both cases, the pathways are deduced from Eulerian data.

Though these prior Eulerian studies identified particular ISOW pathways, no study to date has validated these pathways from a Lagrangian perspective, primarily because Lagrangian data has been so limited. Additionally, no previous study has assessed the temporal interplay among the spreading branches. Thus, the goals of this paper are to: (1) provide a comprehensive description of the ISOW spreading pathways in a combined Eulerian and Lagrangian frame; (2) shed light on the interplay between spreading pathways on interannual time scales. Specifically, we use previously unreported current meter data from two different arrays, two sets of CTD stations, RAFOS float data and a high resolution model output to: (1) identify ISOW in the Iceland Basin; (2) trace different ISOW spreading pathways; (3) quantify the volume transport and measure the relative importance of different ISOW branches; and (4) assess the temporal variability of the spreading pathways.

The paper is organized as follows: We review ISOW pathways from previous studies in Section 2 and summarize our data sources and methods in Section 3. In Section 4, we provide a comprehensive description of the major ISOW export pathways out of the Iceland Basin and in Section 5, we quantify the different pathways from both Eulerian and Lagrangian perspectives. Conclusions follow in Section 6.

2. Prior knowledge of the Iceland Scotland Overflow Water pathways and their transports

Iceland Scotland Overflow Water (ISOW) enters the eastern subpolar North Atlantic between Iceland and Scotland primarily through the Faroe-Shetland Channel (FSC) (Hansen and Østerhus, 2007) and a minor part over the Iceland-Faroe Ridge (Beaird et al., 2013) (Fig. 1). After flowing through the FSC, one ISOW branch flows into the Iceland Basin through the Faroe Bank Channel, filling the bottom layer (density ≥ 27.80 kg/m^3 with a depth range from 1300 m to the bottom) on the Icelandic Slope (Saunders, 1996; Kanzow and Zenk, 2014; Xu et al., 2010). Another branch travels southward into the Rockall Trough across the Wyville-Thomson Ridge (WTR) (Chang et al., 2009; Ellett and Roberts, 1973; Sherwin and Turrell, 2005). A small branch flows southward west of the Maury Channel (Chang et al., 2009; Xu et al., 2010). As ISOW spreads southward and westward, it mixes with lighter subtropical waters carried by the North Atlantic Current (NAC), Labrador Sea Water (LSW) from the western subpolar gyre, and Lower Deep Water (LDW) from the south (van Aken, 1995; McCartney, 1992).

Direct measurements of the transport in the ISOW layer are available at limited locations (labeled in magenta in Fig. 1). The FBC overflow is measured to be 2.1–2.2 Sv (1 Sv = 10^6 m^3/s) (Hansen and Østerhus, 2007; Hansen et al., 2016) and the overflow over the IFR is estimated to be > 0.8 Sv (Beaird et al., 2013). A southward transport of 3.2–3.8 Sv is observed in the ISOW layer along the northwestern slope of the basin south of Iceland (Saunders, 1996; Kanzow and Zenk, 2014). A transport of 0.1–3.0 Sv with large uncertainties through the Rockall Trough is estimated by Dickson and Brown (1994), while a more recent study shows that the transport across the WTR is at the lower bound of the range (Sherwin et al., 2008). A westward transport of waters in the ISOW layer across the Charlie Gibbs Fracture Zone (CGFZ), measured with mooring arrays, is 1.7–2.4 Sv (Saunders, 1994; Bower and Furey, 2017). However, this branch is highly variable due to the frequent approach of the eastward-flowing NAC (Schott et al., 1999; Bower and Furey, 2017), whose deep flow field interacts with the westward transport of ISOW. The transport of waters denser than 27.80 kg/m^3 in the southward branch along the eastern MAR flank from the Iceland Basin to the West European Basin (WEB) has been estimated to be 2.4–3.5 Sv from tracer data (Fleischmann et al., 2001).

In addition to the Eulerian-based studies, past Lagrangian studies have also investigated the spreading of intermediate and deep waters in the Iceland Basin. With passive neutrally buoyant RAFOS floats (released between 1419 and 2866 dbar), Lankhorst and Zenk (2006) identify three major pathways of LSW in the Iceland Basin: westward escape into the Irminger Sea through the Bight Fracture Zone (BFZ) along the RR (see also Bower et al., 2002); eastward flow across the CGFZ, which is the major exchange gateway of LSW between the Irminger Sea and the Iceland Basin; and a southward spreading along the eastern flank of the MAR (see also Machín et al., 2006). Though these pathways are mostly identified in the LSW layer, which is shallower than the ISOW layer, the pathways across the RR gaps and along the eastern flank of the MAR are similar to those observed in the ISOW layer (as detailed below), indicating a barotropic structure for the spreading of intermediate and deep waters.

A number of modeling studies have also estimated the volume transport of different ISOW branches (labeled in magenta with parentheses in Fig. 1). For example, Xu et al. (2010) estimate that the total transport of ISOW along the northwestern slope south of Iceland is 3.3 Sv. The cross-RR transport in the ISOW layer is estimated to be 1.2 Sv and the westward transport through the CGFZ is 1.9 Sv. Another modeling study (Chang et al., 2009) also gives the estimate of the ISOW layer transport west of the Maury Channel (1.5 Sv), within the Rockall Trough (2.2 Sv), and into the WEB (4.6 Sv). Most of these model-based estimates compare fairly well with observational estimates except for the transport estimate into the WEB.

However, to our knowledge, there is to date no observational or modeling study that describes these ISOW branches from a Lagrangian perspective, nor one that investigates the time-varying relationship among the different ISOW branches. The current research aims at filling those gaps and intends to shed light on the similarities and differences between the Eulerian-based and Lagrangian-based studies of ISOW spreading pathways and transports.

3. Data and methods

3.1. Mooring array and CTD stations in the central Iceland Basin

To identify ISOW and its transport cores in the Iceland Basin, we use a mooring array (M1, D1, D2, D3, M2, D4, M3 and M4 in Fig. 1) and a set of CTD stations (black dashed line in Fig. 1) across the Iceland Basin at 58-59°N. The mooring array and the CTD stations constitute part of the Overturning in the Subpolar North Atlantic Program (OSNAP) - East section, which extends from the southern tip of Greenland to Scotland (Lozier et al., 2016).

The mooring array was deployed in July 2014 across the entire Iceland Basin at depths between 699 m and 2830 m. Here we use the mean velocity and property profiles at depths ≥ 1000 m from the first year of measurements to study the ISOW transport. On the same cruise, CTD measurements were conducted across the OSNAP section. CTD data at depths ≥ 1000 m along the eastern flank of the RR, where the ISOW major branch is located, is also used in this study.

3.2. Mooring array and CTD stations east of CGFZ

Another mooring array used in this study is located to the east of the CGFZ. The moorings, labeled C, G, F, Z, M, A, R and T are shown in Fig. 1. Moorings C, G, F and Z were deployed on June 25, 1999 and largely recovered on July 1, 2000. Moorings M, A, R and T were