A New Paradigm for Atlantic Ocean Deep Water Formation

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Outline

The Atlantic Meridional Overturning Circulation (AMOC), a key mechanism in the climate system, transforms warm and salty waters from the subtropical gyre into colder and fresher waters in the subpolar gyre and Nordic Seas. For over three decades, the Labrador and Nordic Seas were considered as the sources for the AMOC lower limb, but recent observations revealed a minor contribution of the Labrador Sea convection to the total overturning of the subpolar gyre. In this study, we show that the prevailing sources are shifted to the Iceland Basin and Irminger Sea. A first direct estimate of air-sea heat and freshwater fluxes over these basins reveals the key role of these fluxes in establishing the state of the AMOC. The overturned water is however not entirely exported seasonally, and the maximum volume of water exported out of the basins by horizontal circulation lags the peak of transformation by five months.

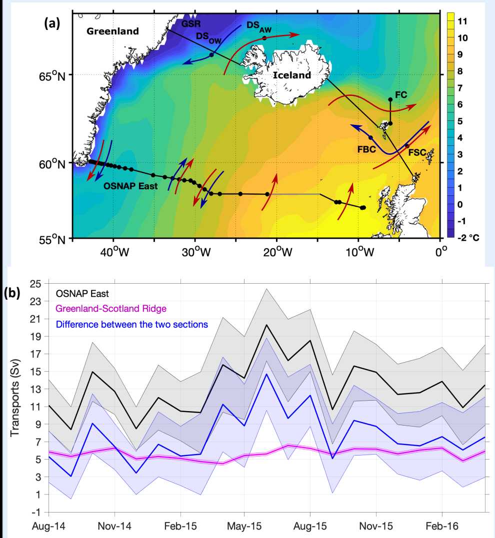


Fig. 1: (a) Map of sea surface temperature (°C) during the OSNAP period showing mooring locations along OSNAP East and along GSR for 1) Atlantic inflows at Denmark Strait (DSAW), Faroe-Shetland Current (FSC) and Faroe-Current (FC) and 2) for overflows at Denmark Strait (DSOW) and Faroe-Bank Chanel (FBC). The grey line at OSNAP East shows the glider survey region. Red and blue arrows depict upper and lower flows, respectively. (b) 30-day mean transports (positive southward) integrated in the lower layers at OSNAP East (black line) and GSR (magenta line) and their difference (blue line). Shading indicates uncertainty in means.

Spatial pattern of transformation rates

Transformation rates induced by air-sea fluxes were estimated over the surface density range of the North-Atlantic subpolar gyre following the method of (1) Walin (1982) from ERA5 and NCEP atmospheric reanalysis:

→ Transformation rates at 27.55 kg m^{-3}, the averaged AMOC density at OSNAP East, show that the Irminger Sea boundary and Reykjanes Ridge are two hotspots with persistent outcropping that play a key role in the transformation of light to dense waters between OSNAP East and Greenland-Scotland Ridge (GSR).

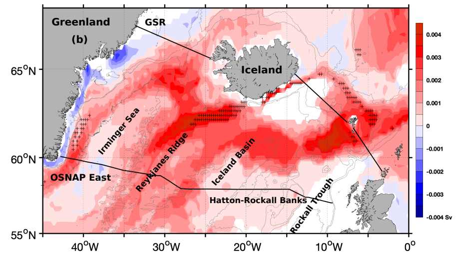


Fig. 2: Transformation rates (Sv) at 27.55 kg m^{-3} over the Irminger Sea and Iceland Basin averaged over the 21-month OSNAP observations. Positive transformation rates (red) are associated with densification to the isopycnals. Black crosses indicate outcropping areas of the isopycnals during all 8 months of winter (December to March) 2014–2015 and 2015–2016.

(1) Walin, G. (1982). On the relation between sea-surface heat flow and thermal circulation in the ocean. *Tellus*, *34*, 187–195

Densification due to buoyancy forcing over the OSNAP period

The overturning in the Iceland Basin and Irminger Sea is estimated by computing the volume budget for the upper and lower layers from the volume fluxes at OSNAP East and GSR over the 21 months of OSNAP observations:

- The volume exchange between the layers is estimated to be **7.5 to 8.0** $\pm$ **3.8 Sv**;
- This estimate is in close agreement with the transformation rate of **7.0** $\pm$ **2.5 Sv** across the monthly-varying isopycnal that separates the lower and upper AMOC limbs;

➢ **The large volume overturned in the Irminger and Iceland basins north of OSNAP East is thus mainly explained by the buoyancy forcing.**

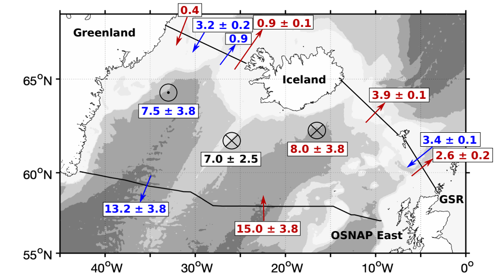
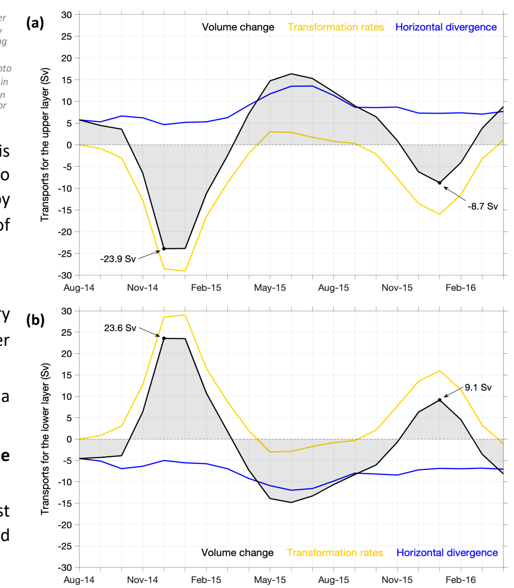


Fig. 3: Volume budget of the upper (red) and lower (blue) layers between GSR and OSNAP East. Transports (Sv) were averaged over the OSNAP period, except for the upper East Greenland Current (0.4 Sv) and the lower North Icelandic Irminger Current (0.9 Sv), which were averaged from September 2011 to August 2012 following Chafik & Rossby (2019). The transport in black is the average transformation rate (Sv) across the monthly-varying isopycnal that separates the lower and upper AMOC limbs. Bathymetry is shaded for 500, 1000, 2000 and 3000 m.

Temporal variability of the overturning in the Iceland and Irminger basins

Fig. 4: 30-day mean volume change (Sv) in the (a) upper layer and (b) lower layer between OSNAP East and GSR (black lines). The volume change is estimated by combining the transformation at the AMOC isopycnal through air-sea flux forcing (Sv, yellow lines) and the horizontal divergence of transport into each layer as estimated in Fig. 1b (Sv, blue lines). The three variables are positives for inflows into the layer, such that positive transformation rates are associated with lightening in the upper layer and densification in the lower layer. Positive shading indicates an accumulated volume in the layer and negative shading indicates a volume lost for the layer. The products are smoothed over three months.



Over the 21 months of OSNAP observations, the variability of the overturning between OSNAP East and GSR is large, with a 30-day mean range of 3.1 ± 2.6 Sv in September 2014 to 14.7 ± 4.1 Sv in June 2015 (Fig. 1b). To analyze this variability, the change in the layer volume is estimated for the upper and lower layers by combining the transformation due to air-sea fluxes and the horizontal divergence of volume into and out of each layer.

The change in volume for the lower layer takes place in two steps (Fig. 4):

- The accumulation of dense water in the lower layer during winter, with a maximum of 23.6 Sv in January 2015, is explained by a strong densification of the upper layer (29.1 Sv) and a weak export out of the lower layer (-5.1 Sv) → The lower layer gains more than it loses.
- The export of dense water the following five months is due to a decrease of the buoyancy forcing and a strengthening of the export during summer → The lower layer loses more than it gains.

Thus, the maximum volume of water exported out of the lower layer by the horizontal circulation lags the peak of densification by five months.

Over a year, volume change by densification from air-sea flux transformations is larger than volume lost through horizontal divergence. This implies that part of the overturned water is stored in the Irminger and Iceland basins and is not exported seasonally, such that **3.8 Sv is stored f**rom August 2014 to July 2015.