Rapid Entrainment-Forced Freshening of the Iceland Scotland Overflow

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Key Points:

- Significant freshening of the Iceland Scotland Overflow plume is observed in the Iceland Basin
- Salinity changes in the overflow plume are directly linked to changes in the upper ocean through entrainment
- Entrainment significantly modifies North Atlantic deep water mass properties on sub-decadal timescales.

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Abstract

Newly available mooring observations from the Overturning in the Subpolar North Atlantic Program (OSNAP) show an abrupt decline in Iceland Scotland Overflow (ISOW) salinity from 2017 to 2018 summer. Previous declines in ISOW salinity of similar magnitude have largely been attributed to changes in convectively formed deep waters in the Nordic seas on decadal time scales. We show that this rapid decline in salinity was driven by entrainment of a major upper ocean salinity anomaly in the Iceland Basin. This is shown by tracking the propagation of the upper ocean anomaly into ISOW using a combination of mooring and Argo observations, surface drifter trajectories, and numerical model results. A 2-year total transit time from the upper ocean into the ISOW layer was found. The results show that entrainment allows for rapid modification of ISOW, and consequently the lower limb of Atlantic Meridional Overturning Circulation, on sub-decadal timescales.

Plain Language Summary

New observations from the Overturning in the Subpolar North Atlantic Program (OSNAP) show a major decline of deep ocean salinity in a layer known as the Iceland Scotland Overflow (ISOW). The ISOW layer is an important component of the deep ocean circulation in the North Atlantic formed through a mixing of cold, deep water from the Nordic Seas and salty, mid-depth water in the Atlantic. Previously recorded salinity changes of similar magnitude in the ISOW layer have occurred over timescales greater than a decade. This ISOW freshening event is traced back to a major freshening of the upper ocean that propagated into the ISOW layer through entrainment, a process of intense mixing between deep and mid ocean waters. Using a combination of numerical model output, Argo and surface drifter data, and moored observations, we show that entrainment facilitated a significant change to the ISOW layer in just 2-3 years.

1 Introduction

Iceland Scotland Overflow Water (ISOW) is a major constituent of the Atlantic Meridional Overturning Circulation's southward, abyssal flow. ISOW is formed from warm, salty upper ocean waters delivered to the North Atlantic Subpolar Gyre and Nordic Seas via the North Atlantic Current (NAC) (Hansen & Østerhus, 2007). After its formation, ISOW is exported out of the Iceland Basin through gaps in the Mid Atlantic Ridge and mixes with other deep water masses to form North Atlantic Deep Water, the dominant southward flowing water mass in the AMOC. Understanding the drivers of variability in ISOW is therefore critical to understanding variability in the whole AMOC system.

Hydrographic variability within the abyssal ISOW layer is linked to its source water masses. Two distinct processes converge to form ISOW: convection in the Nordic Seas and entrainment along the Iceland Faroe Ridge (IFR). Convection transforms warm, salty upper ocean water into cold, dense, deep water in the Nordic seas, which then flows southwards across the IFR (Johns et al., 2021-Under Review; Hansen & Østerhus, 2007; Fogelqvist et al., 2003; García-Ibáñez et al., 2015).The majority of the Nordic Seas overflow crossing the IFR is funneled through the Faroe Bank Channel (FBC) before spilling into the Iceland Basin. Entrainment occurs as the flow spills out of FBC and descends into the abyssal layer as a gravity current (Hansen & Østerhus, 2000, 2007). This process mixes warm, salty upper ocean waters into the overflowing waters, creating the final ISOW water mass. Cumulatively across the entire IFR, the entrainment process nearly doubles the total transport from 3 Sv of the original Nordic Seas overflow crossing the IFR to 5.3 Sv (Johns et al., 2021-Under Review). The similar volumetric contributions of convectively formed deep water and entrained waters into the overflow implies that property variations in either the overflow waters or entrained waters can have a significant impact on the final ISOW properties.

Newly available mooring observations from the Overturning in the Subpolar North Atlantic (OSNAP) show major upper ocean subpolar gyre freshening, followed by an abrupt decline in ISOW salinity 2 years later. The upper ocean freshening event was the most intense salinity decline observed in 120 years and was driven by changes in subpolar gyre circulation (Holliday et al., 2020). The OSNAP observations raise the question: Did the upper ocean event force the ISOW freshening, and if so, through what mechanisms? We demonstrate here the upper ocean's ability to force substantial hydrographic variability in ISOW on sub-decadal timescales through the entrainment pathway. The pathway is defined as the upper ocean NAC and the abyssal ISOW layer flow connected by entrainment at Faroe Bank Channel.

Multiple upper ocean freshening events in the subpolar gyre have been documented in the last 100 years. Previous efforts to track the propagation of these events show 3-6 year upper ocean advection times from the gyre to the Nordic Seas (Belkin, 2004). However, the lack of abyssal layer observations prevented past studies from linking singular upper ocean events to changes in abyssal waters such as ISOW. Dickson et al. (2002) showed that a decadal scale decline of ISOW salinity in the 1990's was due to widespread freshening in the regions of deep water formation north of the subpolar gyre. They suggest that entrainment acted to reinforce changes already present in the convectively formed overflow waters. However, the recently observed decline of salinity in the ISOW plume occurred just 2 years after the upper ocean freshening event and was as large in magnitude as the decade long decline described by Dickson et al. (2002). This strongly points to entrainment as the mechanism responsible for the recent ISOW freshening.

To demonstrate that entrainment of the upper ocean salinity anomaly was the cause of the ISOW freshening, we tracked the anomaly's propagation along the expected entrainment pathway. A combination of Argo derived salinity fields, surface drifter trajectories, and the FLAME (Family of Linked Atlantic Model Experiments) ocean model are used for tracking the anomaly and investigating its pathway. Our methods are detailed in the next section followed by the results along each segment of the entrainment pathway, and concluding remarks on the implications of this study.

2 Data and Methods

2.1 OSNAP mooring array

The OSNAP mooring array crosses the entire North Atlantic subpolar gyre, capturing the upper and lower limbs of the AMOC (Lozier et al., 2019). Here we focus on the OSNAP-East section which crosses the Iceland Basin from the Reykyanes Ridge to the Hatton Bank (Fig. 1) . The array provides hourly hydrographic measurements of the NAC and ISOW flows from July 2014 to July 2018. For a detailed description of the entire OSNAP array readers are referred to Lozier et al. (2019), and to Johns et al. (2021-Under Review) for further details on the OSNAP-East section. The eastern side of the array, mainly moorings M3 and M4, sample the northward flowing NAC waters while the western side captures the southward, bottom trapped ISOW (Fig. 1). For this study we utilize the instruments in the upper 300 meters of the mooring array to represent the near surface waters of the Iceland Basin, and the near-bottom instrument at each mooring to represent the ISOW properties. These measurements capture the salinity anomaly as it is advected across the OSNAP line but give no further details on the advective pathways through the basin. For this we turn to surface drifters, Argo derived hydrography, and results from a numerical model.

2.2 Surface Drifters and Super-trajectories

Surface drifter trajectories, at hourly resolution, from the AOML Global Surface Drifter Dataset are used to investigate the upper ocean connection of the NAC to the region of the FBC sill where entrainment occurs (Elipot et al., 2016). All trajectories from drogued in the Iceland Basin from 2005-2018 are used to construct a transit matrix for a 0.25° x 0.25° grid of the eastern subpolar gyre. The transit matrix approximates the probability of a particle moving from any particular grid cell to any other cell over a fixed timescale (Ser-Giacomi et al., 2015; McAdam & Sebille, 2018).

Using the transit matrix, we simulate super-trajectories in a Markov Chain Monte Carlo simulation that moves particles across the grid by using the probabilities contained in the transit matrix (Sebille et al., 2011; Ser-Giacomi et al., 2015). We simulate 10^4 trajectories to thoroughly sample the distributions of drifter movements. Further detail on the construction of the transit matrix and super-trajectories can be found in Supporting Information-S1.

Trajectories are initiated in the NAC upstream (south) of the OSNAP line before the current turns northward and splits into several branches. From this set of trajectories, we focus the analysis on those which reach the ”entrainment zone”, a region immediately downstream of the FBC sill (indicated in Fig. 3). By initializing the trajectories upstream of the OSNAP line we can identify all the advective pathways connecting the NAC to FBC and their associated timescales.

2.3 Argo Climatology

The Roemmich-Gilson Argo (RGA) monthly analysis is used to observe the time evolution of salinity in upper ocean NAC waters downstream of FBC where the bulk of entrainment occurs. The RGA analysis has a 1°x1° resolution and spans 2004-2018 (Roemmich & Gilson, 2009). Using the grid point closest to the FBC (9.5°W, 61.5°N), a time series of salinity anomalies is constructed. The salinity anomalies are calculated relative to the 2014-2018 mean, matching the period of the OSNAP records. The record is also de-seasonalized to remove the effects of seasonal precipitation anomalies that impact the upper ocean salinity across the entire subpolar region.

2.4 FLAME model trajectories

Output from the Family of Linked Atlantic Model Experiments (FLAME) is used trace the flow in the ISOW layer southwards to the OSNAP line. These model simulations were used as part of investigations into downstream ISOW pathways by Gary et al. (2011); Zou et al. (2017). Drifters were released every 3 months from 1992 to 1994 at various depths within the ISOW layer (i.e at depths below the 27.8 kg/m^3 isopycnal) in the two main branches of ISOW flow at the OSNAP line and their trajectories were computed backwards in time for 24 months. The upper ridge branch and a basin interior branch were identified in the observational studies by Zou et al. (2017) and Johns et al. (2021-Under Review). Although FLAME output does not span the OSNAP observational record, sensitivity experiments show that advective pathways are representative of typical ISOW flow and should not affect our major conclusions (Gary et al., 2011).

The trajectories are forced with the 3-D velocities at 3 day time steps, integrated backwards in time until reaching the vicinity of the FBC sill. Only trajectories reaching the FBC entrainment zone were included in the analysis. These trajectories provide an estimate of the typical pathways and typical timescales of particles in the ISOW plume that travel southward from the FBC to the OSNAP line.

3 Results

3.1 OSNAP Observations

The OSNAP array shows a major upper ocean decline in salinity beginning in July 2015 (Fig. 2a). Freshening occurs first on the eastern side of the array, in the NAC. Upper ocean salinity minima are observed in November 2015 and March 2017 at the location of mooring M3. The magnitude of freshening varies over the time between these two minima but the salinity anomaly remains negative through this period. Meanwhile on the western side of the array, negative anomalies arrive in May 2016 and persist through the end of the record. This is consistent with the freshening signal being advected around the Iceland basin, following the cyclonic subpolar gyre circulation. The cause of this upper ocean salinity anomaly was shown by Holliday et al. (2020) to be linked to an anomalous diversion of freshwater from the Labrador Shelf into the the NAC, combined with wind driven circulation changes. We are focused on the propagation of this anomaly into the ISOW layer. Salinities within the ISOW layer abruptly decline beginning in January

2017, first at M1 near the crest of the Reykjanes Ridge, followed by freshening eastward across the basin. Negative anomalies spread eastward across the array, reaching D5 by July 2017, near the eastern limit of the ISOW plume. After the initial arrival of the freshening pulse in March 2017, positive salinity anomalies occur at D2-D4 for a 2-3 month period before resumption of an overall freshening trend. Salinities continually decrease across the entire array through the end of the record with nearly all moorings showing a greater than 0.01 PSU decline. We believe the freshening observed in the eastern Iceland Basin is related to the recirculation and mixing of ISOW into the region rather than direct pathways from the FBC overflow to the eastern part of the basin (Johns et al., 2021-Under Review). The overall 2 year decline in salinity of ISOW is comparable in magnitude with the "Great Salinity Anomaly" decadal scale freshening event of the 1990's documented by Dickson et al. (2002).

The OSNAP observations show a 1.5-2 year lag between upper ocean and overflow layer freshening. If the upper ocean anomaly is forcing the ISOW changes, this lag provides an estimate of the advection time from the NAC entering the Iceland Basin to the ISOW being exported southwards from the basin. Below we examine the advective pathway in three stages: northward advection to Faroe Bank Channel, entrainment into the overflow, and southward advection to the OSNAP line within the ISOW layer. By constructing a timeline of this pathway and comparing it with the estimated lag from the OSNAP array we can verify that entrainment is responsible for the ISOW freshening.

3.2 Advection within the NAC to Faroe Bank Channel

The drifter derived super-trajectories show the advective pathway connecting the North Atlantic Current to Faroe Bank Channel, the first limb of the entrainment pathway. Figure 3 shows the frequency of super trajectory positions for trajectories that reach the entrainment zone. The highest frequencies are seen following the eastern Iceland Basin topography north eastwards towards the Faroes. This agrees well with the known paths of the North Atlantic Current and the Hatton/Rockall Bank jets. The trajectory distributions also extend eastward towards the western side of the Rockall Trough but do not indicate a significant pathway to the FBC directly through the Rockall Trough.

To further dissect the various branches associated with the NAC to FBC connection, we can examine the longitudinal distributions of the trajectories and the associated advection times. The distribution of super-trajectories crossing 58°N shows two peaks, a main peak centered near 24°W and a secondary peak near 20°W. The larger peak, accounting for 65% of trajectories, crossing the OSNAP line between 26-22°W, indicates that the NAC branch through the Iceland Basin delivers the bulk of upper ocean waters to the entrainment zone. Advection times from the OSNAP line to FBC in this branch range between 2-8 months. The smaller peak, 20% of trajectories, indicates a narrow branch of flow between 21-19°W which advects waters to FBC within 2-4 months. This narrow and faster branch occurs in the region of the Hatton Bank Jet, shown by Houpert et al. (2018) to be a region of enhanced northward NAC flow trapped aliong the eastern slope of the basin. The super-trajectory results suggest that these two NAC branches reaching FBC deliver 80% of particles in 2-8 months, with an average arrival time of 4.8 months.

3.3 Entrainment into the Iceland Scotland Overflow

The RGA reconstruction of salinity anomalies at FBC clearly shows the arrival of the freshening signal and its downward propagation to entrainment depths. Figure 4 shows the arrival of negative anomalies in the upper 300 meters in October 2015, 3 months after freshening at the OSNAP array. The timing of this freshening is consistent with the shorter end of the advective timescales estimated from the super-trajectories. However, the actual entrainment only occurs at depths of 600-800 meters, corresponding to the depths of the overflow layer as it spills out of the FBC (Hansen & Østerhus, 2007). Through winter and spring of 2016 the freshening signal propagates down to entrainment depths, where it persists through the summer of 2018. The downward propagation of the salinity anomaly is likely associated with Subpolar Mode Water formation, a seasonal process occurring through much of the northern Iceland Basin (Brambilla & Talley, 2008; Brambilla et al., 2008). The delayed arrival of negative salinity anomalies at depth could also be partly due to slower subsurface advective speeds in the NAC compared to those at the surface. The continuous negative salinity signal at depth shows that the overflow was entraining anomalously fresh waters from spring 2016 through summer 2018. In combination with the super trajectories, the Argo record shows that anomalies entering the Iceland Basin in the NAC are entrained into the overflow approximately 6-12 months after they are advected to FBC and mixed to sufficient depth.

3.4 Southward Propagation in the Iceland Scotland Overflow Plume

Once entrained, the upper ocean freshening signal propagates within the Iceland-Scotland Overflow plume's pathway along the eastern flank of Reykjanes Ridge. We cross-correlated salinity anomaly records at every bottom mooring with the RGA time series at 600 meters in Figure 4 to estimate the lag between salinity changes at FBC and in the overflow layer at the OSNAP array. A maximum correlation is seen at M1 ($r=0.42$, at $P<0.05$) with a 7-8 month lag. The bottom M1 record lies in upper part of the ISOW layer, closest to the Reykjanes Ridge crest. Weaker correlations are also present with mooring records to the east down the ridge slope with generally longer lags. This is consistent with model-based evidence presented below that indicates longer and more circuitous pathways of flow in the ISOW layer towards the Iceland Basin interior.

We applied an 8 month shift to the RGA salinity record at FBC for a closer comparison with the salinity record at M1 (Fig. 4). There is some variability in the apparent arrival times of salinity anomalies in the ISOW plume, with the initial onset of the freshening trend at M1 occurring in January 2017, about 10 months after it began at the entrainment site, and the large freshening anomaly at the end of the M1 record, in July 2018, appearing to occur about 7 months after the maximum freshening anomaly at the entrainment site in November 2017. These variations can be explained in part by the low temporal resolution of the RGA dataset as well as internal variability of the ISOW plume. Combined with the upper ocean transit time to the entrainment zone, we estimate an approximate total 1.5-2 year advection time from the NAC crossing the OSNAP line in the upper ocean to ISOW being exported southward out of the basin. This fits well with the lag observed in Figure 2, however the results also raise two key questions: Is a 7-10 month lag consistent with the ISOW flow, and why does the freshening signal take longer to arrive in the interior of the Iceland Basin?

3.5 ISOW pathways in FLAME

The FLAME model results display the variable ISOW flow pathways through the Iceland Basin (Fig. 5). Backward pathways from the upper branch of the ISOW plume to the FBC sill follow the topography of the Reykjanes Ridge and the Iceland Faroe Ridge. The 5-9 month advection times in the upper branch agree well with the M1 cross-correlation estimated times (Fig. 5; b-inset). Mooring records at several locations along the Reykjanes Ridge confirm a more laminar, consistently southward flow close to the ridge axis (Kanzow & Zenk, 2014; Johns et al., 2021-Under Review). Basin interior branch trajectories follow the Iceland Faroe Ridge and then detach from the topography as the flow turns southward along the RR. The basin interior trajectories are longer and more circuitous than those in the upper branch. This results in longer, more variable advection times of 12-18 months from FBC to the OSNAP array. The longer advection times found in the basin interior branch of ISOW flow explain the delayed onset of freshening across the ISOW layer (Fig. 2b). Onset of freshening on the eastern side of the basin (near M4) is likely explained by horizontal mixing associated with energetic, quasi-isotropic variability in the central Iceland basin as well as sub-basin recirculation recirculations evident in the mooring array data (SI-S3).

The model results and the OSNAP records suggest that the advection time from FBC out of the Iceland Basin ranges from 6 months near the Reykyanes Ridge to >15 months in the basin interior. Combined with the upper ocean advective timescales of

6-12 months, this shows that salinity anomalies in the upper ocean can modify the entire ISOW layer in 1.5-2 years.

3.6 Salinity Signal on the Convective Pathway

Past studies of salinity anomalies in the ISOW layer show longer timescales of propagation from the upper ocean into ISOW that are linked primarily with changes in the convectively formed Norwegian Sea Overflow Waters. During the time period of this freshening event, mooring observations in the Norwegian Sea Overflow layer in the Faroe Bank Channel, upstream of entrainment, show no significant, sustained, freshening signal as of the most recent recovery of data from FBC in the summer of 2018 (Personal Communication; B. Hansen 2019). Additionally, Argo observations in the Norwegian Sea do not show the arrival of a freshening signal until January 2017 (SI, Fig. S3), and the signal fails to penetrate depths greater than 600 meters through the summer of 2018. Both sets of observations show that overflow waters in the Nordic Seas have not yet been significantly freshened to explain the observed freshening. The presence of fresher waters in the upper ocean of the Norwegian Sea suggests that convectively formed deep waters here may eventually carry the freshening signal to FBC. However, it is unclear if or when that signal may appear clearly in the overflow waters. Complex deep Norwegian Basin and Greenland Sea circulation and stabilizing effects of the deep water reservoir feeding the overflows suggest that convection does not directly link the upper and deep flows in the same manner as entrainment (Shao et al., 2019).

Finally, we consider whether the magnitude of the ISOW freshening signal is consistent with the magnitude of the upper ocean freshening event, via the process of entrainment. Johns et al. (2021-Under Review) show the final ISOW product contains about 25% of entrained Subpolar Mode Water. If entrainment of the upper ocean anomaly is the main cause of the $O(0.01)$ PSU ISOW freshening, this would imply a salinity decline of 0.04 PSU in the Subpolar Mode Water that is entrained into the overflow. Figure 4 shows freshening on the order of 0.02-0.06 PSU at the level of entrainment into the overflow at the FBC, which is consistent with the above estimate. Therefore, the initial salinity anomaly of the near-surface waters of the Iceland Basin of $O(0.1$ PSU), after being diluted by vertical mixing down to the level of entrainment at FBC (0.04 PSU), can explain the $O(0.01$ PSU) freshening of the ISOW layer through entrainment of about a 1:4 volume ratio of SPMW into the final ISOW product watermass. If freshening of overflow waters does occur in the future while entrained waters remain anomalously fresh, the ISOW freshening may be expected to increase in the next years to decade.

4 Conclusions

Our results demonstrate that the recently observed freshening in the Iceland Scotland Overflow waters was caused by entrainment of a major upper ocean salinity anomaly. Upon entering the Iceland Basin, anomalously fresh waters took about to 6-8 months to reach the entrainment zone near Faroe Bank Channel and propagate down to depths of active entrainment. Once entrained, the salinity anomaly took 1-1.5 years to spread southward in the ISOW layer back to the OSNAP line, leading to total advection time of 1.5-2 years. The combined effects of entrainment and the associated currents allow for rapid and significant modifications to ISOW and, consequently, North Atlantic Deep Water salinity on a sub-decadal timescale. Previous studies have repeatedly highlighted the AMOC's sensitivity to salinity changes (Josey et al., 2018; Hátún et al., 2005). Future work from a more basin wide perspective can be used to investigate the downstream North Atlantic Deep Water and AMOC response to this rapid ISOW salinity freshening event.

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Data Availability Statement

OSNAP data used in this study are available online at https://www.o-snap.org/observations/data. Datasets for this research are available in these in-text data citation references: Roemmich and Gilson (2009), Johns et al. (2021-Under Review), and Elipot et al. (2016).

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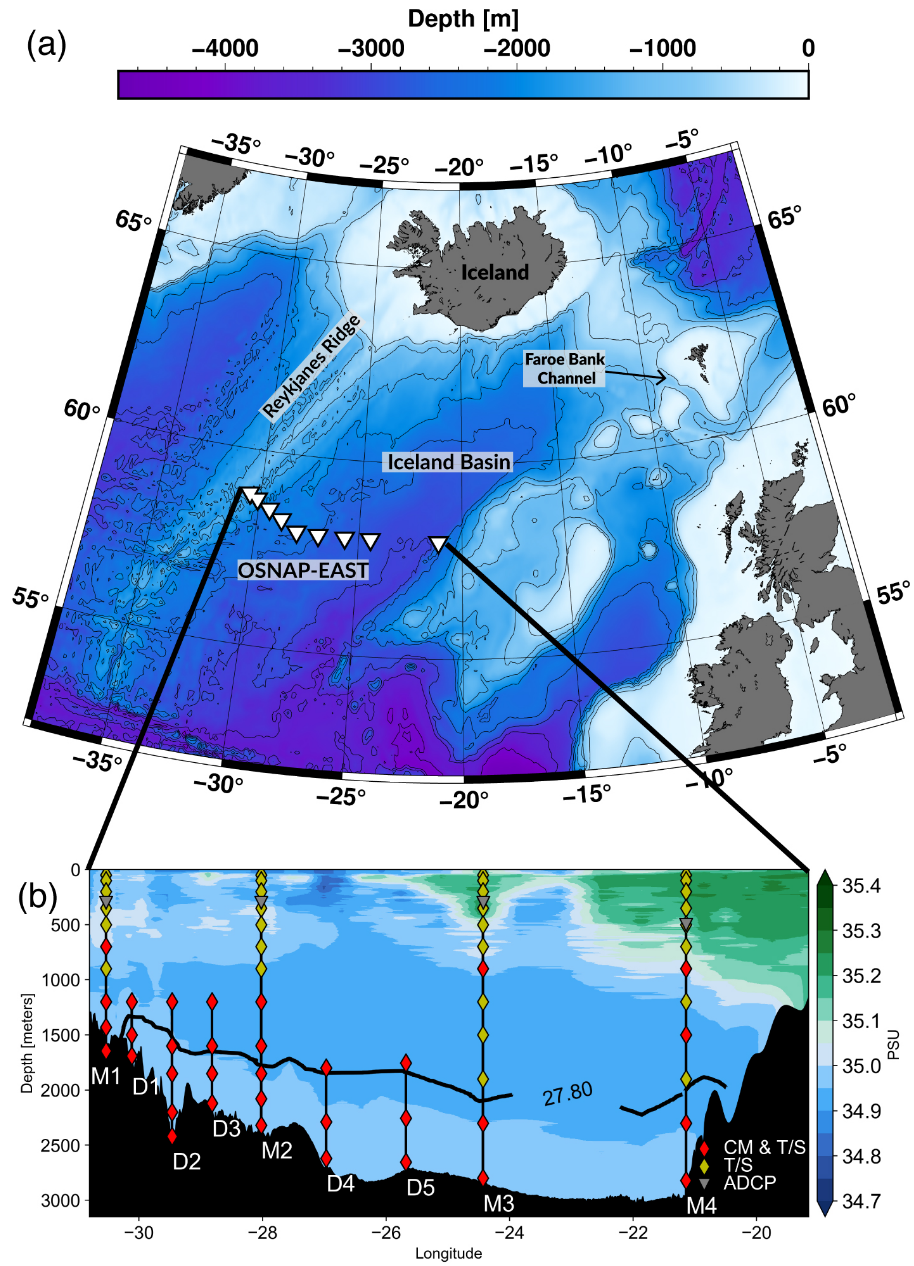

Figure 1. (a) Topographic map of the Iceland Basin and Iceland Faroe Ridge, with depth contours at 500 meter intervals. OSNAP mooring line indicated in red. (b) Configuration of the OSNAP-East mooring array with contours indicating salinity (PSU) from the 2018 OSNAP hydrographic section. Depths of temperature/salinity recorders, current meters, and ADCP's are indicated on each mooring.

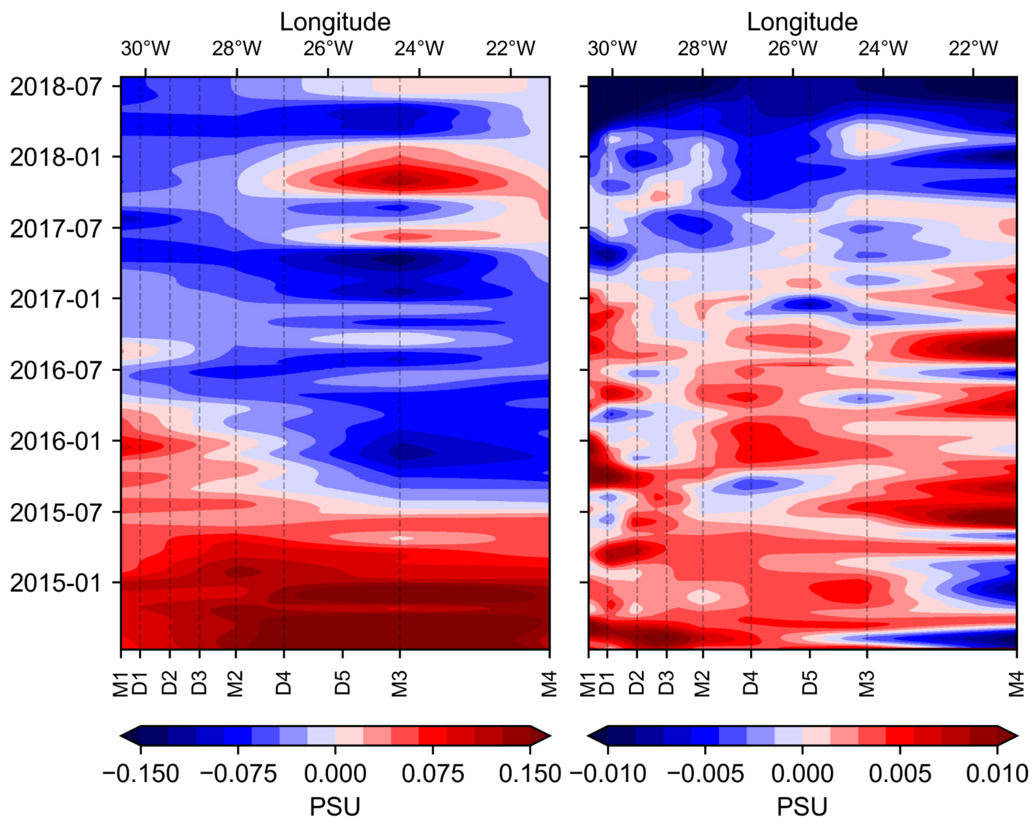

Figure 2. Hovmöllers of Mean OSNAP-EAST salinity anomalies (PSU) averaged over the upper 300 meters (left) and near-bottom (right). Data is at hourly resolution with a 60 day low-pass filter applied to both time series. Dashed lines indicate data coverage at each mooring. Note the different scales for the two plots, reflecting the larger range of salinity variability in the upper ocean. Anomalies are relative to the record mean (July 2014 - July 2018).

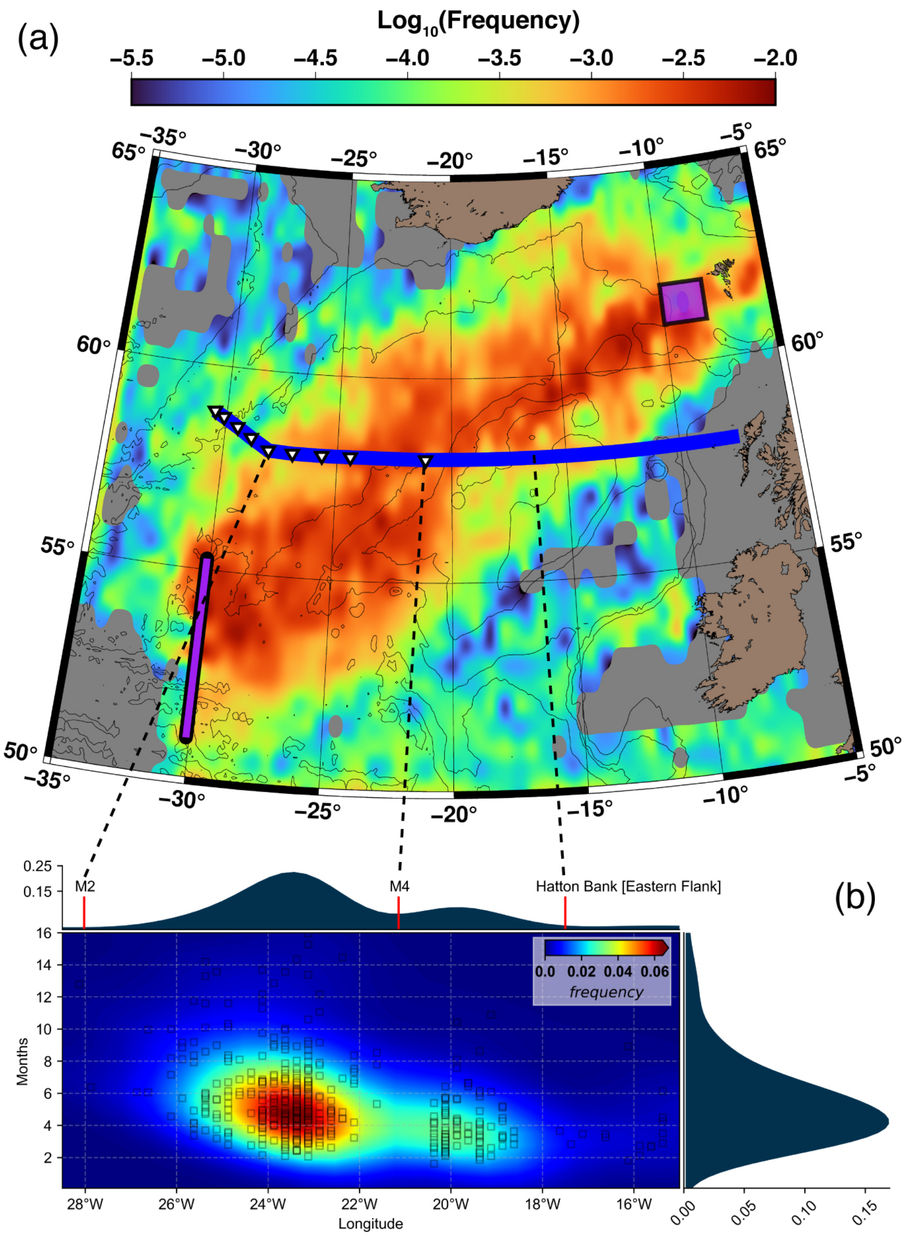

Figure 3. (a) The frequency distribution of simulated super trajectories released in the NAC (purple line) that reached the entrainment zone at Faroe Bank Channel (purple box). (b) The longitudinal distribution of trajectories crossing the The OSNAP line (blue line in a) vs. the advection time from the OSNAP line to the entrainment zone. The histograms along the top and right sides show the distributions of crossing longitudes and advection times to Faroe Bank Channel, respectively. OSNAP mooring locations are marked with triangles.

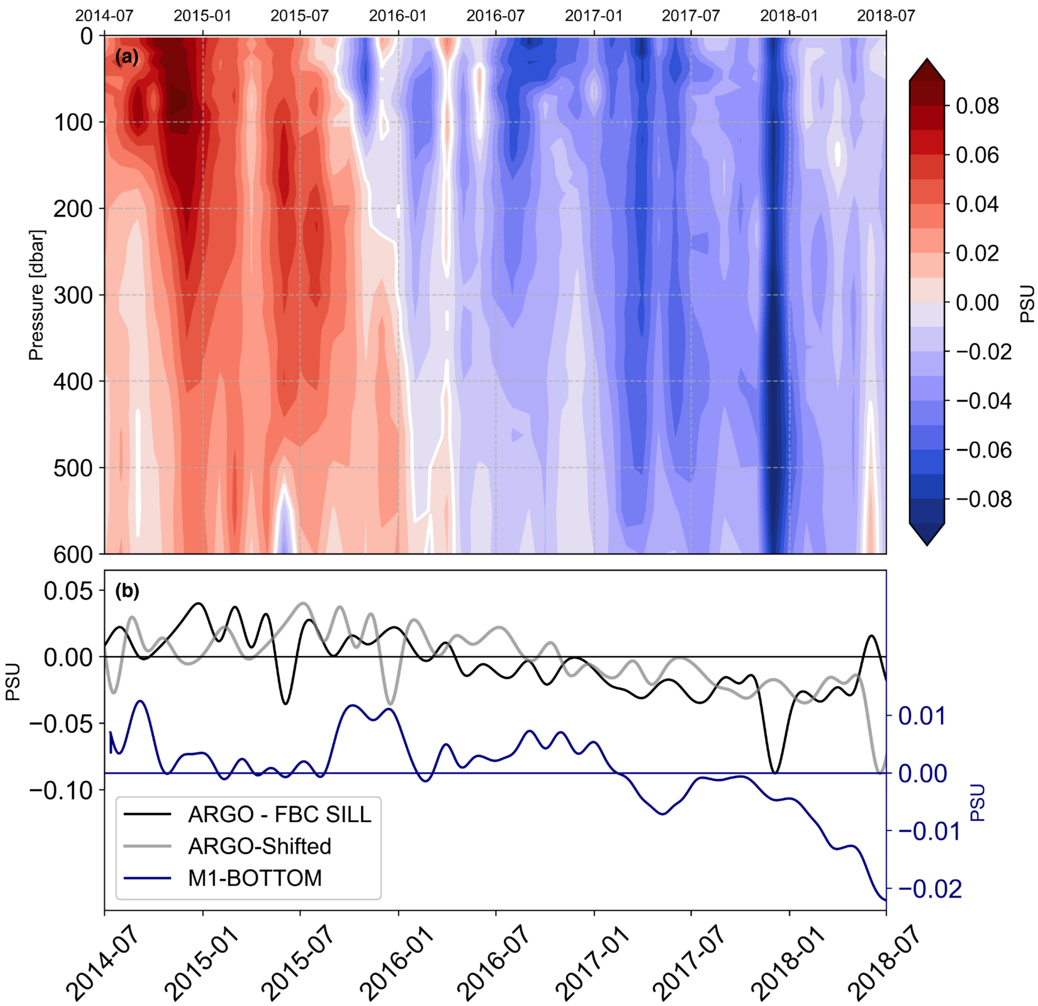

Figure 4. (a) Time series of salinity anomalies at the closest RGA grid point downstream of the FBC overflow sill (see Figure 1). Anomalies are relative to the July 2014-July 2018 mean, matching the OSNAP record's coverage. The seasonal cycle has been removed to reduce influence from intense seasonal air-sea fluxes in the region. (b) RGA salinity anomaly time series at 600 meters depth (black-solid) and at the M1 near bottom salinity record (blue). The gray line is the 8-month shifted RGA time series. These time series are taken from the grid point closest to the FBC sill at 9.5° W, 61° N

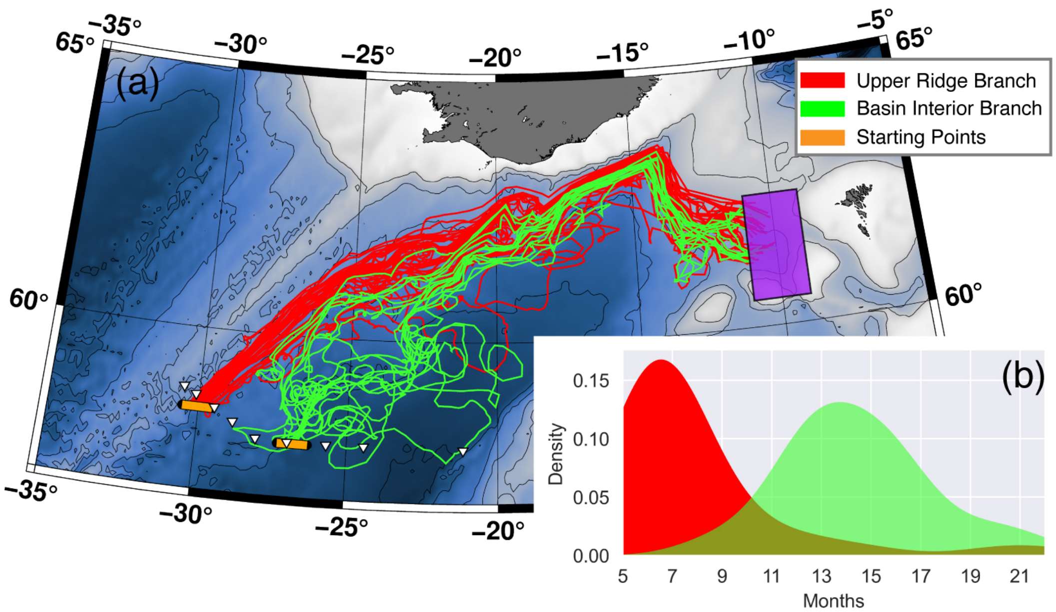

Figure 5. (a) FLAME model trajectories integrated backwards in time, released from the regions of moorings D1-D2 (red) and D4 (green). Orange bars indicate the range of longitudes where drifters were released. Trajectories are shown from their release sites back to the FBC sill. (b-inset) Histograms of advection times from FBC to the OSNAP line, with same color designation as the trajectories.