Dense water pathways feeding the Faroe Bank Channel Overflow

1. Introduction

The overflow of dense water across the Greenland-Scotland Ridge (GSR), and its subsequent entrainment, is a critical component of the Atlantic Meridional Overturning Circulation (AMOC) which helps maintain Earth's climate (Buckley and Marshall, 2016). Together with the convected product formed in the Labrador and Irminger Seas, the cold dense water constitutes North Atlantic Deep Water which is transported equatorward in the Deep Western Boundary Current as the lower limb of the AMOC. One of the open issues regarding the magnitude and variability of the AMOC is its relationship to high-latitude deep water formation. Earlier studies argued that subpolar mode water formed south of the GSR is key in driving the interannual variability of the AMOC (e.g., Böning et al., 2006), and the IPCC attributes the projected 21st century slowdown of the AMOC to decreases in deep convection in the Labrador Sea (IPCC, 2013). However, observational evidence of such a causal relationship is lacking (Lozier, 2012), and recent results demonstrate that the contribution to the AMOC from the Labrador Sea is small (Lozier et al., 2019). This puts renewed importance on understanding the warm-to-cold transformation that takes place in the Nordic Seas (e.g., Chafik and Rossby, 2019) and the pathways and mechanisms by which the newly ventilated dense water is exported across the GSR.

Over the past decade, a series of studies has greatly enhanced our view of the dense water feeding the overflow through Denmark Strait. This has included the identification of the North Icelandic Jet (NIJ) flowing along the north slope of Iceland that transports up to half of the overflow water entering the strait (Våge et al., 2011; Semper et al., 2019; Lin et al., 2020). A year-long mooring array deployed across the northern part of Denmark Strait demonstrated that there is temporal partitioning on monthly timescales between the NIJ and the two East Greenland Current branches of overflow water feeding the strait, such that the total dense water transport remains relatively constant (Harden et al., 2016). By comparison, however, our knowledge of the dense water feeding the eastern overflow through the Faroe Bank Channel still has fundamental gaps. While historical measurements have produced rudimentary circulation schemes, several recent studies have identified previously unknown pathways of dense water presumably being advected into the channel. However, the observational evidence of these new pathways is based on a patchwork of non-contemporaneous data sources that is far from complete, and the studies have raised as many questions as they have answered. Since the Faroe Bank Channel overflow accounts for roughly half of the total overflow transport across the GSR, it is of high importance to determine and quantify its sources and the mechanisms by which the water progresses from its ventilation region to where it overflows the GSR. The formation of the water (i.e., the warm-to-cold conversion) and mixing along the pathways dictate the temperature of the final product and hence strongly impact the AMOC heat flux. Improving our understanding of these things, including their sensitivity to atmospheric forcing, is critical in order to predict how the AMOC will respond to a warming climate.

Herein we propose a high-resolution mooring array to quantitatively measure, for the first time, what appears to be the main conduit of dense water feeding the Faroe Bank Channel overflow. Accompanying shipboard surveys will trace the flow upstream to its source region(s), and also document its downstream path and evolution to where it overflows in the Faroe Bank Channel. We will augment the observations with modeling and simple theory to provide dynamical context. The proposed work is part of a larger international program to address the pathways and mechanisms by which dense water is supplied to the eastern GSR, through coordinated observations and modeling. Researchers from seven institutions comprise the team, each bringing considerable resources and expertise. Together, this will fundamentally advance our understanding of this important component of the AMOC. The name of our collaborative program is "**U**pstream Pathways of the **F**aroe **O**verflow" (UFO).

2. Background and Motivation

The Faroe Bank Channel overflow (FBCO) supplies the densest water to the North Atlantic. At the sill, which is ~850 m deep, the long-term mean transport is 1.9 ± 0.3 Sv (Østerhus et al., 2019). Seasonally the transport is strongest in summer and weakest in winter (Chafik et al., 2020). Entrainment downstream of the sill significantly boosts the transport (Mauritzen et al., 2005), and, based on four years of mooring data far downstream in the Deep Western Boundary Current, the transport is 5.5 ± 0.5 Sv, on par with the entrained transport of Denmark Strait overflow water (Pacini et al., 2020). The sources and pathways of the FBCO water have been a topic of research for more than a century. However, while different aspects of the contributing water masses and their circulation have emerged over the years, there remain numerous critical knowledge gaps. As motivation for the present proposal, a number of previous findings are now discussed where we highlight some of the unknowns to be addressed by the proposed project. Figure 1 shows a large-scale basemap of the Nordic Seas with the relevant currents and topographic features.

2.1 Dense water source regions

It has been argued that the dense water feeding the FBCO stems partly from four sources: the Arctic Ocean, the Greenland Sea, the Iceland Sea, and the Norwegian Sea. The Arctic Ocean source enters the Nordic Seas via Fram Strait in the East Greenland Current (e.g., Aagaard et al., 1985; Rudels et al., 1998). This dense water then branches eastward, presumably in the Jan Mayen Current (Shao et al., 2019; Fig. 1), which enters the Norwegian Sea (Mauritzen, 1996) and ultimately feeds the Faroe-Shetland Channel on its way to the overflow. The Greenland Sea source is the cyclonic gyre within that basin, where intermediate to deep wintertime convection forms sufficiently dense water to supply the FBCO (Olsson et al., 2005). Applying the so-called “sigma-pi distance” method to an extensive historical hydrographic database, Huang et al. (2020) showed that the water mass properties of the densest FBCO water match closely with the newly ventilated water in the Greenland Sea Gyre. Jeansson et al. (2017) argue that, subsequent to leaving the gyre, this water mixes with some of the saltier Arctic Ocean source water (see also Blindheim and Adlandsvik, 1995 and Fogelqvist et al., 2003).

Dense water formed in the Iceland Sea is also believed to contribute to the FBCO (Jeansson et al., 2017). This dense water is formed both within the Iceland Sea Gyre via wintertime convection (Swift and Aagaard, 1981; Våge et al., 2015) and farther south in the vicinity of the north slope of Iceland (Read and Pollard, 1992). It is thought that this water progresses into the Norwegian Sea via the East Icelandic Current (Read and Pollard, 1992; Blindheim and Rey, 2004; Macrander et al., 2014; Fig. 1), although Mauritzen (1996) argue that the water primarily feeds the Iceland-Faroe Ridge overflow rather than the FBCO. Finally, using historical hydrographic data, Eldevik et al. (2009) argued that the FBCO water includes a significant contribution from the Norwegian Sea via a local overturning loop in the Norwegian Basin. This notion is in contrast to the above-mentioned hydrographic analysis of Huang et al. (2020) who demonstrated that the bulk of FBCO water cannot originate in the Norwegian Basin. Hence, despite the plethora of previous water mass studies, there is still considerable uncertainty/disagreement regarding the major source(s) of the dense water supplying the FBCO.

2.2 Dense water pathways

Far-field circulation

A comparable degree of uncertainty surrounds the kinematic pathways and dynamics by which the dense water makes its way to the FBCO. Various studies have suggested that both the dense water stemming from the Arctic Ocean and the dense water formed in the Greenland Sea progress into the Norwegian Sea through the Jan Mayen Channel (Swift and Koltermann, 1988; Sælen, 1990; Aagaard et al., 1985; Mauritzen, 1996; Olsson et al., 2005; Shao et al., 2019; see Fig. 1). Moored measurements in the channel have indicated

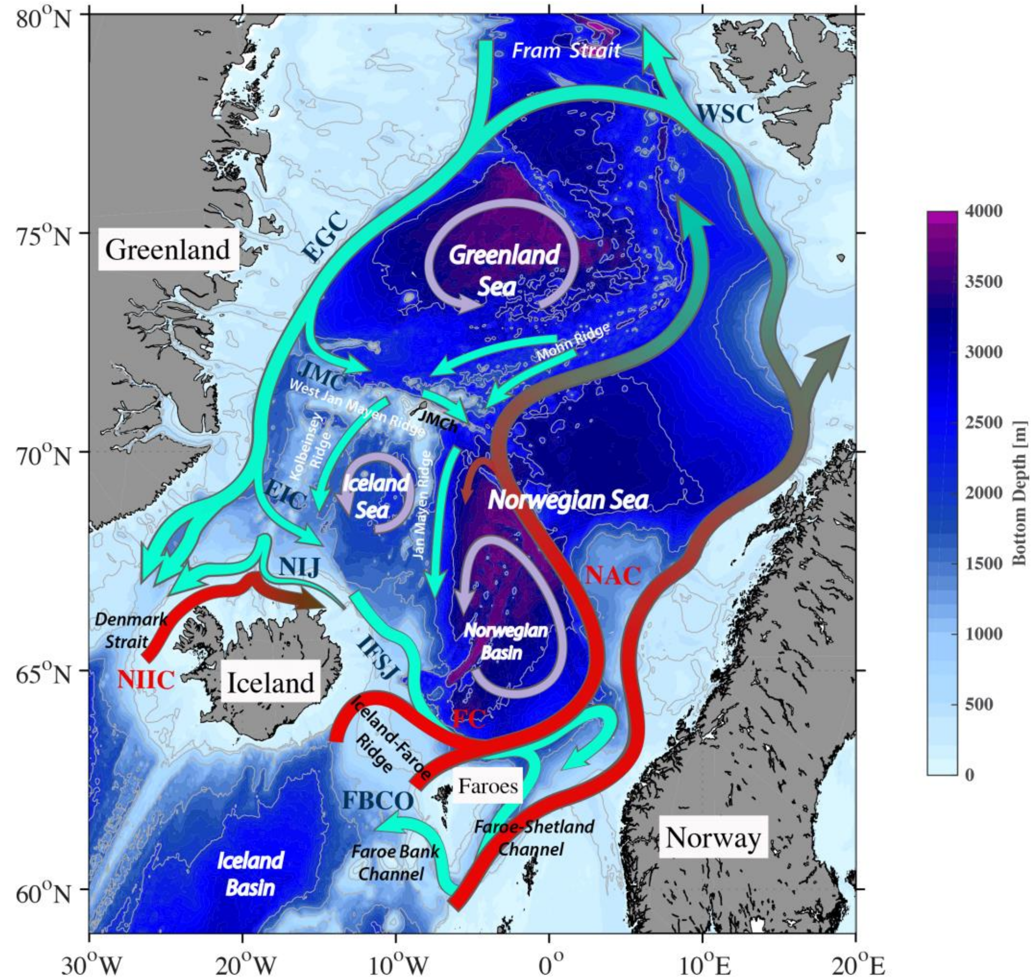

Figure 1: Schematic circulation of the Nordic Seas including place names. The red arrows denote warm currents and the aqua arrows denote cold currents. The three gyres are indicated by the circular arrows. The abbreviations are as follows: NAC, Norwegian Atlantic Current; WSC, West Spitsbergen Current; EGC, East Greenland Current; JMC, Jan Mayen Current; EIC, East Icelandic Current; NIIC, North Icelandic Irminger Current; NIJ, North Icelandic Jet; IFSJ, Iceland-Faroe Slope Jet; FC, Faroe Current; JMCh, Jan Mayen Channel.

eastward flow (Swift and Koltermann, 1998; Sælen, 1990), and Shao et al. (2019) estimated the eastward transport of cold water in the channel to be 1.6 Sv, comparable to the FBCO transport. Such a conduit of dense water is also consistent with the advective-diffusive model of Olsson et al. (2005). Upon exiting the channel, the dense water is thought to turn to the right and progress southward as a boundary current along the edge of the Jan Mayen Ridge (e.g., Sælen, 1990; Mauritzen, 1996; Fig. 1). Shao et al. (2019) suggest that the dense outflow from the channel forms a cold reservoir outside of the channel mouth with hydrographic properties similar to those of the FBCO.

In contrast to the above ideas, an alternate scheme exists for how the dense water progresses from the Greenland Sea to the Norwegian Sea, which does not involve significant flow through the Jan Mayen Channel. The above-mentioned sigma-pi distance analysis of Huang et al. (2020) indicated the presence of a pathway in which the dense water from the Greenland Sea Gyre is exported southward along the eastern side of the Mohn Ridge and then continues southward along the Jan Mayen Ridge (Fig. 1). Huang et al. (2020) also presented kinematic evidence of this pathway using absolute geostrophic velocities referenced using satellite altimetry data. Such a pathway is consistent with the model results of Köhl (2010) using a general circulation model and Yang and Pratt (2014) using a two-layer model with realistic bathymetry.

Note that in this scheme the flow does not respond to the topography of the Jan Mayen Channel, but rather jumps this narrow gap. However, both schemes involve a dense water boundary current flowing southward along the Jan Mayen Ridge.

A similar quandary exists for how dense water progresses from the Iceland Sea to the Norwegian Sea. The earlier water mass studies mentioned above invoked the East Icelandic Current, which branches off of the East Greenland Current and flows eastward along the north slope of the Iceland Sea (Fig. 1). Macrander et al. (2014) investigated the structure and transport of this surface-intensified current, but confined their analysis to depths shallower than 170 m. It is possible that the deeper portion of the current advects dense overflow water into the Norwegian Basin. This idea seems to be supported by the RAFOS float trajectories of de Jong et al. (2018) where four of the floats ballasted for 500 m exited the Iceland Sea in a relatively narrow band where the East Icelandic Current is thought to be located. This is also generally consistent with the Argo float trajectories presented in Voet et al. (2010). However, two recent studies have identified dense water pathways in the Iceland Sea distinct from the East Icelandic Current. Huang et al. (2020) revealed a southward-flowing boundary current on the eastern side of the Kolbeinsey Ridge (Fig. 1). This pathway also emanates from the Mohn Ridge, and, like its counterpart flowing southward along the Jan Mayen Ridge, transports water similar in hydrographic properties to the FBCO. Additionally, Semper et al. (2020) identified a bottom-intensified current on the northeast slope of Iceland that continues eastward along the north side of the Iceland-Faroe Ridge. While this current, which they named the Iceland-Faroe Slope Jet (IFSJ; Fig. 1), also advects water matching the FBCO, its source(s) remains unknown.

Circulation in the vicinity of the Iceland-Faroe Ridge

Previous studies have implied the existence of the IFSJ. Hopkins et al. (1992) reported on the results from three moorings spaced along the 1000 m isobath on the north side of the Iceland-Faroe Ridge. At each site the mean flow was directed eastward along the slope. This is consistent with more recently obtained mooring data from the continental slope north of the Faroe Islands (Semper et al., 2020; Fig. 2a, purple vector). The Lagrangian study of Søiland et al. (2008) analyzed RAFOS floats ballasted at 800 m depth along the north side of the ridge. Notably, all of the floats (with one exception) launched over bottom depths shallower than 1750 m progressed along the ridge into the Faroe-Shetland Channel and subsequently into the Faroe Bank Channel. By contrast, all of the floats launched over deeper isobaths remained in the Norwegian Basin, tracing out a generally cyclonic pattern. Based on this, Søiland et al. (2008) concluded that all of the water supplying the FBCO stems from the Iceland-Faroe Ridge, with no contribution from the Norwegian Basin. Interestingly, two of the RAFOS floats deployed in the Iceland Sea, discussed in de Jong et al. (2018), surfaced close to the Faroe Bank Channel, implying connectivity from the Iceland Sea to the overflow along the Iceland-Faroe Ridge.

In summer 2011 a detailed hydrographic/velocity survey was carried out by Co-PI Pickart, extending from Iceland to the Faroe Islands, to elucidate the deep circulation of the region. This provided the first detailed view of the IFSJ. Semper et al. (2020) analyzed the data and revealed that the current has two branches, one centered near the 750 m isobath and the other in the vicinity of the 1100 m isobath (the red and black arrows, respectively, in Fig. 2a). The current is weakly bottom-intensified and located beneath the surface-intensified eastward flow of subtropical-origin water (which becomes the Faroe Current as it merges with another subtropical branch close to the Faroe Islands, see Figs. 1 and 2b). Semper et al. (2020) demonstrated that the hydrographic properties of the IFSJ closely match those of the FBCO, and that the current can account for at least half of the FBCO volume transport. However, this is just a single quasi-synoptic survey and it remains unclear why there are two branches, if/how the branches connect to the far-field dense water pathways discussed above, and whether, in the mean, the jet actually accounts for most of the FBCO transport. Notably, on the two eastern-most 2011 hydrographic transects across the Iceland-Faroe Ridge, there is evidence of an even deeper branch (grey vectors in Fig. 2a). This offshore flow could also be part of the FBCO story (see next section).

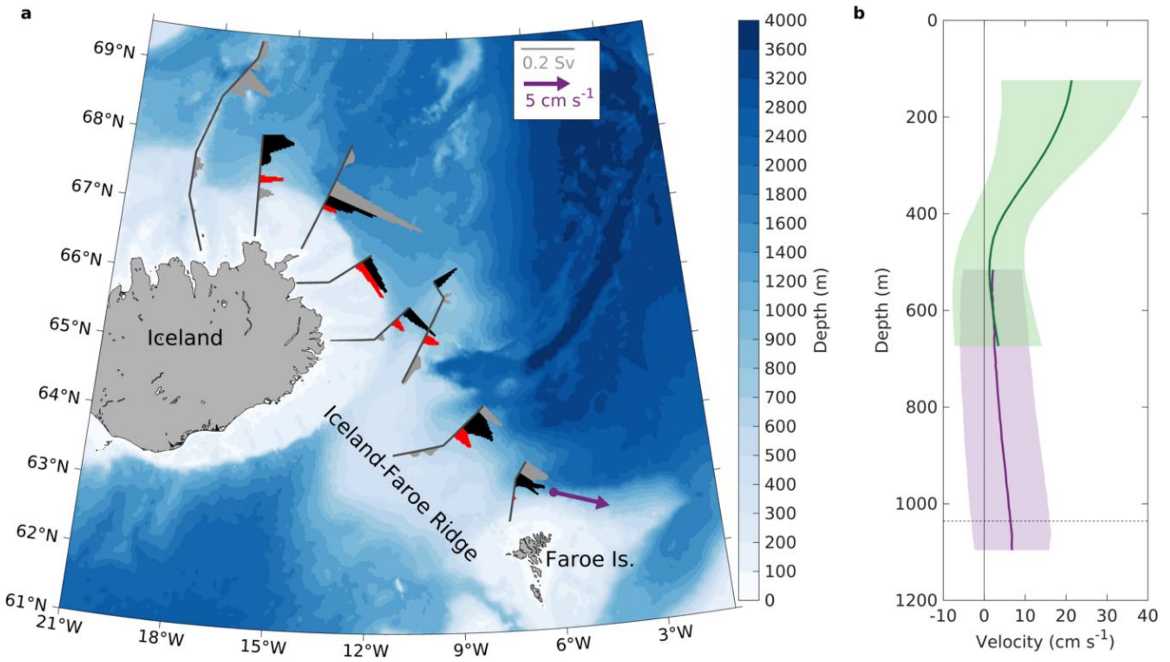

Figure 2: (a) Results from the 2011 shipboard survey which led to the discovery of the IFSJ (from Semper et al., 2020). The arrows along the transects are transport per unit width of the two IFSJ branches (red arrows: 750 m branch; black arrows: 1100 m branch). Evidence of a third deeper branch are seen by the grey arrows at the two eastern-most transects. The year-long mean deep velocity from a mooring near the 1000 m isobath north of the Faroe Islands is shown (purple vector, from Semper et al., 2020). (b) Year-long mean alongstream velocity versus depth at the site north of the Faroe Islands. The different colors are records from two different moorings deployed near each other. The shading is the standard deviation.

2.3 Variability of the dense water circulation

Using data from two moorings located very close to one another on the continental slope north of the Faroe Islands near the 1000 m isobath (one sampling the deep part of the water column and the other sampling the shallow part, Fig. 2b), Semper et al. (2020) investigated the temporal variability of the IFSJ. The dominant empirical orthogonal function (EOF) mode of alongstream velocity corresponded to a seasonal signal in which the IFSJ and upper-layer Faroe Current vary in phase, with stronger velocities in the winter months. The second EOF mode was associated with shorter timescale fluctuations, on the order of 2-3 weeks, in which the two currents vary out of phase with each other. While the nature of the high frequency variability is unknown, it is plausible that the seasonal signal is due to wind forcing.

In the numerical simulation analyzed by Chafik et al. (2020), the model equivalent of the IFSJ had a fast barotropic response to changes in the wind stress curl over the Nordic Seas. In particular, anomalously positive (cyclonic) wind stress curl resulted in a stronger IFSJ, and anomalously negative wind stress curl (anti-cyclonic) led to a weaker IFSJ. Furthermore, Chafik et al. (2020) contrasted two periods: the early 1990s (anomalously positive wind stress curl) and the early 2000s (anomalously negative wind stress curl). In each case they computed back-trajectories of numerical floats launched in the Faroe-Shetland Channel. In the first scenario, in addition to being stronger, the IFSJ shifted onshore and emanated from the Iceland Sea slope. In this case the IFSJ directly fed the Faroe-Shetland Channel. In the second scenario, in addition to being weaker, the IFSJ moved offshore and emanated from the Jan Mayen Ridge. Interestingly, during this period the IFSJ overshot the opening of the Faroe-Shetland Channel and flowed to the northeast before eventually retroflecting and entering the eastern side of the channel (Fig. 1). These results appear to be intriguingly consistent with Søiland et al.'s (2008) RAFOS study, where the floats on the shallower isobaths of the Iceland-Faroe Ridge entered the Faroe-Shetland Channel directly, while those on the deeper isobaths drifted past the opening to the channel. In both scenarios presented by Chafik et al. (2020), the dense water ultimately ends up on the eastern flank of the Faroe-Shetland Channel as it approaches the FBCO.

The recent study of Hátún et al. (2021), who used the same numerical simulation as Chafik et al. (2020), focused on the presence of deep-reaching eastward flow seaward of the IFSJ, which they termed the Norwegian Sea Gyre Rim (NSG Rim). (The offshore grey vectors on the two eastern-most Iceland-Faroe Ridge transects in Fig. 2a likely reflect the southern edge of this flow.) Hátún et al. (2021) argued that this flow varies in phase with the model IFSJ in response to variations in wind stress curl. Furthermore, they showed that the composite transport of these two currents is anti-correlated with the FBCO transport; i.e., stronger eastward flow of dense water along the northern slope of the Iceland-Faroe Ridge corresponds to weaker overflow. The reason for this counter-intuitive relationship remains elusive. It is important to note, however, that the model does not resolve the two branches of the IFSJ, and presently there exist no observational transport timeseries of any of these flow branches (the two IFSJ branches or the NSG Rim). Using the ERA5 atmospheric reanalysis data, we computed the climatological monthly wind stress curl for the Norwegian Sea, Iceland Sea, Greenland Sea, and the full Nordic Seas domain. In each case there is a clear seasonal signal with large positive wind stress curl in the cold months of the year and weak (even negative) wind stress curl in the summer months. As mentioned in the Introduction, seasonal partitioning occurs between the dense water pathways feeding Denmark Strait, driven by the seasonally-varying wind stress curl (Harden et al., 2016). In the case of the Faroe Bank Channel, it is unknown if there is any such partitioning between upstream flow components driven by seasonal variations in the windstress curl.

In summary, while past studies have identified different contributing sources of dense water that ultimately supply the FBCO, recent results suggest that the Greenland Sea Gyre is the predominant source of the largest transport mode of the overflow. With regard to circulation patterns, earlier investigations argued that dense water is exported from the Greenland Sea to the Norwegian Sea via the Jan Mayen Channel, and that, in the Iceland Sea, the export occurs via the surface-intensified East Icelandic Current. Both of these are in contrast to new findings that have made a compelling case for north-south topographically steered pathways emanating from the Mohn Ridge in the Greenland Sea, and the bottom-intensified IFSJ along the Iceland-Faroe Ridge transporting dense water eastwards. These pathways advect water that very closely matches the hydrographic properties of the FBCO. It is possible that the two branches of the IFSJ together receive all of the dense water from the different upstream pathways, and, with perhaps a contribution from the NSG Rim, represent the main supply to the FBCO. Furthermore, time-varying partitioning between the flow components could be taking place, due to wind stress curl forcing, that impacts the manner and dynamics by which the dense water feeds the FBCO. All of these issues require further investigation and motivate the joint field program and modeling/theory study proposed here. Together with a team of international researchers contributing extensive expertise and resources, we will fundamentally advance our knowledge of the upstream FBCO sources, pathways, and dynamics, which in turn will shed much light on the deep limb of the AMOC.

3. Proposed fieldwork and modeling/theory

3.1 Hypotheses

(1) The IFSJ is the dominant contributor to the FBCO, advecting dense water mainly ventilated in the Greenland Sea and brought southward by topographically steered pathways that connect to the IFSJ. (2) Seasonal variations in the regional wind stress curl drive exchange between the Norwegian Sea Gyre and the boundary flow, associated with partitioning between the IFSJ branches and the NSG Rim.

3.2 Overview of the project

To address these hypotheses, we propose a mooring array in conjunction with two shipboard surveys extending upstream and downstream of the array, respectively. The mooring array will, for the first time, provide timeseries of both branches of the IFSJ and the NSG Rim. The array will be deployed from autumn 2023 to autumn 2024 and consist of 8 tightly spaced profiling moorings that resolve and bracket the two previously documented IFSJ branches. The NSG Rim will be measured simultaneously by other members of UFO (described below). The location of the array is shown in Fig. 4a, where the magenta stars are the profiling moorings whose configuration in the vertical plane is shown in Fig. 4b. The rationale behind the array configuration is explained in Section 3.4. After the array is deployed, we will carry out a shipboard hydrographic/velocity survey to identify and map the upstream origins of the IFSJ and establish its connection to the Greenland Sea. The following year, after recovering the array, a shipboard survey will be conducted from the array site to the FBCO in order to establish the connection between the IFSJ + NSG Rim and the overflow.

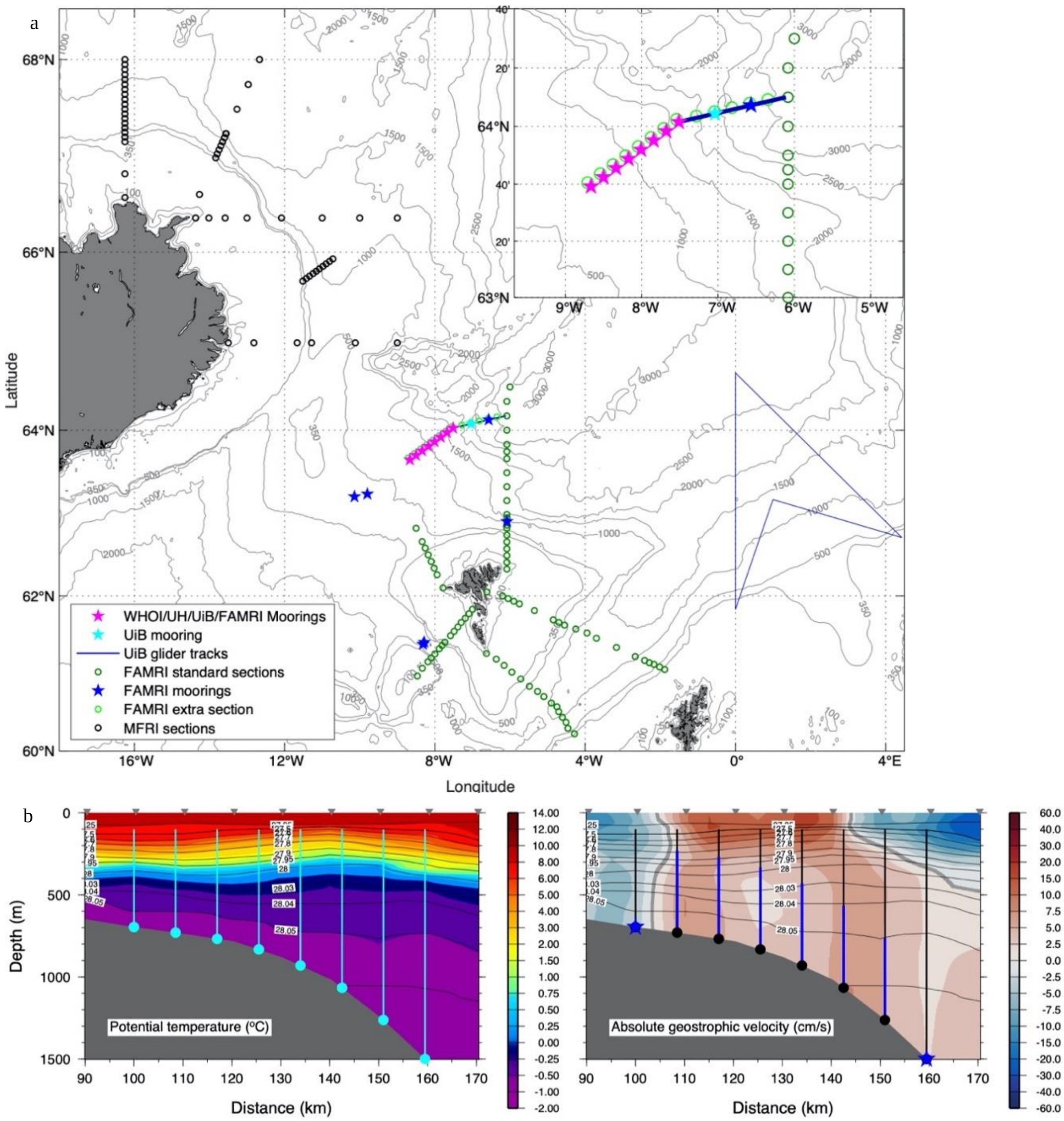

Figure 4: (a) Location of the proposed mooring array, along with the other components of UFO. The WHOI/UH/UiB/FAMRI profiling moorings are the magenta stars, which capture the two previously identified branches of the IFSJ. The glider (blue line) and UiB and FAMRI moorings (cyan and blue stars, respectively) measure the NSG Rim. The other components of the UFO field program (see the legend) are described in the text. The inset shows an enlarged view centered around the composite mooring array. (b) Configuration of the profiling array in the vertical plane, overlain on the shipboard potential temperature section (left) and absolute geostrophic velocity section (right) occupied in 2011 near the array site (the triangles are the 2011 CTD stations). The contours are potential density (kg m^{-3}). The thick blue lines in the right-hand panel denote the ADCP coverage. The blue stars are Aquadopps. The MicroCATs (not shown) are located above and below the MMP bumper stops.

The analysis of the observational data will be closely coordinated with numerical and theoretical approaches. We will make use of (i) a simple theory that identifies the controlling parameters and provides a basic dynamical framework; (ii) idealized model configurations designed to test the theoretically predicted mechanisms and parameter dependencies; and (iii) output from the realistic numerical model of Chafik et al. (2020).

3.3 Scientific Objectives

Objective 1: *To quantify the structure and volume transport of the IFSJ and NSG Rim over an annual cycle and determine the nature and cause of the variability.*

The proposed mooring array will provide the first robust description of the hydrographic and velocity structure of the IFSJ and NSG Rim, and provide an accurate measure of the associated eastward transport. To date only a single shipboard survey has resolved the IFSJ (occupied in summer), and mooring timeseries have been collected at just a few isolated locations (single moorings) where the instrumentation did not span the full vertical extent of the current. The profiling instrumentation employed here will return timeseries of high-resolution vertical sections across the two previously identified IFSJ branches. The NSG Rim, which to date has not been observationally resolved, will be measured by a combination of moorings and a glider provided by other investigators of UFO. The composite array, together with long-term moorings deployed at the Faroe Bank Channel sill (see Section 4), will allow us to determine if the IFSJ branches alone account for the full FBCO transport or if the NSG Rim contributes as well. We will quantify the seasonal hydrographic and kinematic variability of all three flow components along the Iceland-Faroe Ridge, and document if any partitioning occurs between the components due to the wind stress curl forcing. We will also address the nature and cause of the high frequency variability of the IFSJ on timescales of days to weeks, including the role of instabilities and topographic waves. The dynamics of the deep flow will be further investigated using output from the realistic numerical simulation of Chafik et al. (2020), together with an idealized model configuration focused on the interaction of Ekman pumping and exchanges between the Norwegian Sea Gyre and boundary flow, and an accompanying simple theory. This multi-faceted approach is described in Section 3.5.

Objective 2: *To understand the relationship between the IFSJ, the NSG Rim, and the eastward flow of subtropical-origin water in the upper layer, and assess the nature of the coupling to the FBCO.*

The mooring array will extend high enough in the water column to measure the hydrographic properties and eastward flow of subtropical-origin water residing above the IFSJ and inshore of the NSG Rim (this eastward flow eventually becomes part of the Faroe Current). This will allow us to establish if there is a dynamical link between the dense flow and the subtropical-origin flow. Previous results suggest that the height / seaward extent of the interface between the warm, salty water and the dense overflow water varies in phase with the transport of the dense water (Hátún et al., 2021), but this was based on observational proxies due to insufficient data. Previous results also imply that the velocity of the warm, salty water co-varies seasonally with the velocity of the IFSJ (Semper et al., 2020), but this was deduced from data at a single mooring location. Our composite mooring array will allow us to determine if the lateral position, vertical extent, and volume transport of the subtropical-origin flow is in fact related to the deeper flow on a range of timescales, elucidating the interplay between the upper and lower branches of the AMOC at this location. Using the contemporaneous mooring data from FBCO, we will quantify the co-variability of all of these parts of the system. The dynamics of such coupling will be explored using the mooring data in conjunction with the modeling/theory, as described in Section 3.5.

Objective 3: *To more accurately determine the origin and fate of the IFSJ and hence its role in the AMOC.*

New results have provided compelling evidence that the water comprising the dominant transport mode of the FBCO is ventilated in the Greenland Sea Gyre. In addition, this water seems to flow southward from the Greenland Sea along two topographically steered pathways. However, a connection between these two pathways and the IFSJ has yet to be made. One of our shipboard surveys will trace the IFSJ upstream to determine from where the dense water originates and to identify the pathways that link the source region to the IFSJ. This will shed light on why there are distinct branches of the IFSJ. Unlike past surveys, we will employ both direct velocity measurements and the implementation of the sigma-pi distance method at high resolution to reveal the pathways (see Section 3.4 for details on the sigma-pi distance method). We will also use conventional tracers measured from water samples, including oxygen, nutrients, CFC-12, and SF_6 to help put our results in context with historical studies that employed these tracers. The other shipboard survey will use the same approach to map the downstream path and water mass evolution of the IFSJ into the Faroe-Shetland Channel and ultimately to the FBCO. This will address the degree of retroflection that occurs east of the opening of the Faroe-Shetland Channel as well as the transposition of dense water from the western to eastern side of the channel (Chafik et al., 2020). Forward and backward trajectories will be calculated with the realistic model to complement the data analysis regarding the origin and fate of the IFSJ water. The model will also provide long enough timeseries to test the robustness of these pathways in the presence of seasonal and interannual variability, and to identify any dependencies on the patterns of atmospheric forcing, such as the NAO.

3.4 Detailed observational plan

Mooring Array

The location of the mooring array on the Iceland-Faroe Ridge was chosen based on the 2011 shipboard hydrographic/velocity survey that first resolved the IFSJ. The array will be near one of the 2011 sections where the continental slope is gentle, upstream of the standard section occupied by the Faroese Marine Research Institute (FAMRI, see Fig. 4a). We note that it is logistically unfeasible to have the array on the FAMRI line because of the steepness of the continental slope in the isobath range of interest. By using 8 moorings spaced 8-10 km apart – which is the baroclinic Rossby deformation radius – the IFSJ will be bracketed and its two branches resolved (Fig. 4b). Each mooring contains a McLane moored profiler (MMP) with a Sea-Bird SBE37 conductivity-temperature-depth (CTD) sensor and Falmouth Scientific Instruments acoustic current meter (ACM) for measuring velocity. This will provide 4 profiles per day for the shoreward four moorings, and 2 profiles per day for the seaward four moorings, for a year-long deployment. The vertical resolution of all variables is 2 m; hence we will obtain two high-resolution hydrographic/velocity sections per day from 100 m depth to the seafloor, and twice that number of realizations for the shallower branch of the IFSJ. Using velocity profiles from the FAMRI mooring in the Faroe Current, we will design the MMP moorings with enough buoyancy so that blow-downs will be minimal. An additional SBE37 MicroCAT will be positioned immediately above/below each top/bottom stop of the MMPs for increased temporal resolution and for calibration of the MMP data. Half of the MicroCATs are provided by the University of Hamburg (UH). On the central 6 moorings of the MMP array, upward-facing long-ranging acoustic Doppler current profilers (ADCPs) will be positioned at the base of the moorings (Fig. 4b). These will be provided jointly by UH, the University of Bergen (UiB), and FAMRI. On the two endpoint MMP moorings an Aquadopp will measure velocity at the bottom (provided by UH).

To measure the NSG Rim, UiB will operate a Seaglider repeating a line from the offshore-most MMP mooring to the 3200 m isobath (see Fig. 4a) for the same year-long period. According to the numerical model used by Hátún et al. (2021), this will bracket the NSG Rim. As a check on this, we used the historical dataset of Huang et al. (2020) to construct a mean vertical section of absolute geostrophic velocity along the mooring/glider line which showed good agreement with the model results of Hátún et al. (2021). The glider will sample to 1000 m depth with an average horizontal resolution of 5 km, which takes approximately 3 days to occupy. In addition to this, UiB and FAMRI will each deploy a mooring in the NSG Rim (Fig. 4a) using an upward-facing long-ranging ADCP and MicroCAT. Hence, the composite WHOI/UH/UiB/FAMRI moorings plus glider will nicely capture all of the eastward flow potentially feeding the FBCO.

Fishing activity is a concern in the region during the summer months. This is why the top floats of the moorings are situated at 100 m (and not shallower). However, starting in 2016 the fishing activity where the proposed array is situated has decreased markedly. The researchers from FAMRI who are collaborating on UFO are well connected with the local fishing community and will work with them to minimize the risk of damage to the moorings.

Hydrographic cruises

Following the deployment of the mooring array in late-summer 2023, a hydrographic/velocity survey will be carried out investigating the far upstream sources of the IFSJ. A strawperson station plan is shown in Fig. 5 (black squares; although we note that this could be modified as the cruise progresses). The main goals of the survey are to (i) determine if/how the IFSJ is connected to the flow along the Jan Mayen Ridge, the Kolbeinsey Ridge, and the East Icelandic Current (see Fig. 1); (ii) confirm the existence of the southward flow along the Mohn Ridge implied by the historical data of Huang et al. (2020); and (iii) verify that the Greenland Sea Gyre is the predominant source of the dense transport mode of the FBCO rather than the Iceland Sea Gyre.

The following year, after the mooring array is recovered, a second hydrographic/velocity survey will be conducted, this time covering the region from the array to the sill of the Faroe Bank Channel. A strawperson station plan is shown in Fig. 5 (red squares; again, this could be modified during the cruise). This is meant to establish the connection between the IFSJ and the FBCO, including any modification of the dense water advected by the current as it proceeds from the array to the overflow. While previous surveys have addressed the FBCO and the region immediately downstream and upstream of the sill, this will be the first survey to extend far upstream to identify the pathways that feed the Faroe-Shetland Channel. As noted above, the model results of Chafik et al. (2020) suggest that the IFSJ can either flow into the channel directly or overshoot the mouth of the channel before retroflecting and entering the eastern side of the channel. The weakened wind stress curl in summer implies that the latter scenario should be dominant at the time of the cruise. However, Chafik et al. (2020) argue that, regardless of the scenario, most of the inflow to the Faroe-Shetland Channel ultimately forms a well-defined current on the eastern flank of the channel (which they named the Faroe-Shetland Channel Jet). Our survey will investigate both the retroflection and the existence/evolution of this jet. One of the sections extends into the Norwegian Sea Gyre to sample the reservoir of deep water that can potentially contribute to the overflow on a seasonal basis (see Section 3.5).

On both cruises we will collect water samples for measuring oxygen, nutrients, CFC-12, and SF_6, which collectively can be used to identify water mass fingerprints and to compare our results to previous studies. Importantly, the tight station spacing of our transects will resolve all of the currents in question, and the shipboard ADCP data will enable computation of absolute geostrophic velocities and volume transports. Also, the sigma-pi distance method, which is carried out in potential density–potential spicity space (Huang et al., 2018), is extremely effective at identifying and tracking water of similar hydrographic characteristics. As noted above in Section 2, Huang et al. (2020) employed this method using a comprehensive historical

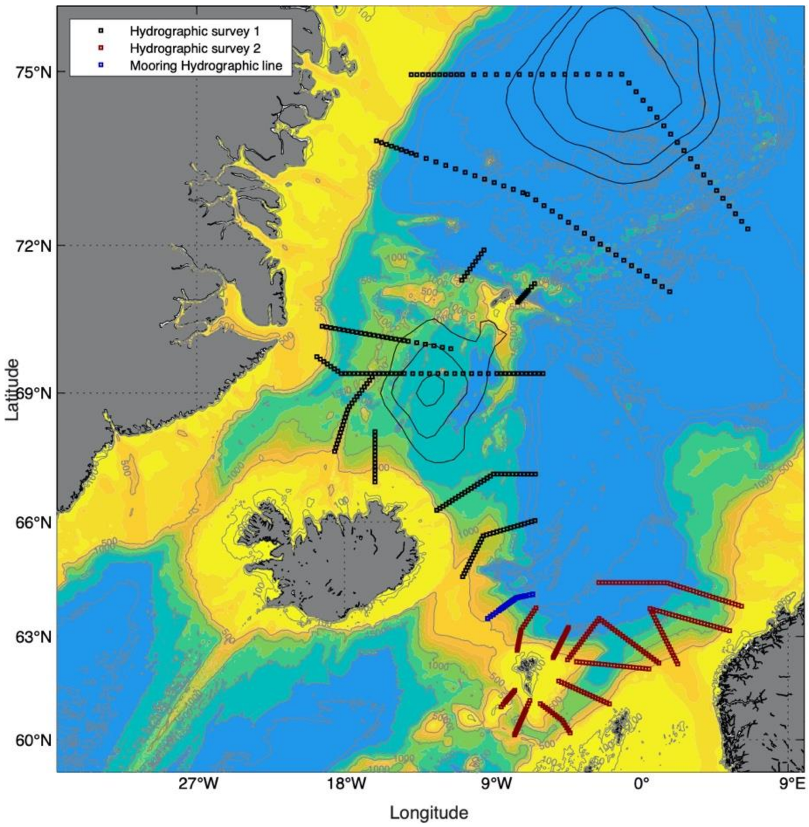

Figure 5: Strawperson station plan for the two hydrographic/velocity surveys (see legend). Sea surface dynamic height contours, relative to 500 db, of the Iceland Sea (IS; 6, 6.5, 7 dyn-cm) and Greenland Sea (GS; 4, 4.5, 5 dyn-cm) Gyres are shown, computed using the historical dataset of Huang et al. (2020). The CTD section along the mooring line is denoted by blue squares. The bathymetry (color and grey contours) is from ETOPO2.

hydrographic dataset to reveal the progression of water from the Greenland Sea to the FBCO via the topographically steered pathways. Since our cruises will take place in late-summer, we carried out the same calculation using only data from Jul-Sep from the historical dataset (representing 35% of the data), which resulted in the same interpretation. As such, the sigma-pi distance results are not sensitive to season. We then applied the sigma-pi distance calculation to two of Pickart's past cruises in the Nordic Seas: the one that elucidated the NIJ (Semper et al., 2019), and the one that elucidated the IFSJ (Semper et al., 2020). Again, the results were very clear and consistent, which demonstrates that any synoptic variability within the time frame of a single cruise will not bias the results.

All of the cruise legs will originate and end from Torshavn, Faroe Islands. On both the deployment cruise and the recovery cruise, the mooring work will be carried out first on a short 7-day leg. To estimate the time required for the hydrographic/velocity surveys we employed a cruise-planner script that Pickart uses on all of his cruises. This indicates that the second leg on the deployment cruise will be 33 days, while that on the recovery cruise will be 28 days. We note that the order of the two surveys is such that the mooring array will measure water sampled during the upstream cruise, while the downstream cruise will sample water measured previously by the array.

Analysis approach

The type of high-resolution boundary current mooring array proposed here has been previously employed by Pickart in the Beaufort Sea, Irminger Sea, Iceland Sea, Labrador Sea, and the Nansen Basin. To address the objectives described above, we will follow a similar approach in the processing and analysis of the data. This includes constructing timeseries of gridded vertical sections of hydrographic properties, along- and cross-stream velocity, and Ertel potential vorticity. These will be used to quantify mean and seasonally-varying aspects of the flow and their relationship to the atmospheric forcing. Mesoscale processes will also be investigated, including instabilities, topographic waves, and wind-forced upwelling and downwelling. Some aspects of the analysis will involve the observations alone, while many of the questions will be addressed jointly with the observations and model/theory. Spall and Pickart have a long history of such collaborative analyses (24 joint model/data publications to date).

The processing and analysis of the shipboard data will also proceed along the lines of previous work. Vertical sections of hydrographic properties, absolute geostrophic velocity, and Ertel potential vorticity, along with lateral maps on both depth and density surfaces, will be constructed to address the objectives. The additional shipboard hydrographic and velocity information from the UFO collaborators (see Section 4) will be combined with our data, which significantly expands the breadth of information. We will also update the historical hydrographic database used by Huang et al. (2020) with the addition of our new data plus other recent cruises to the region.

3.5 Detailed model/theory plan

We will use a combination of theory, idealized models, and a realistic model, in conjunction with the observations, to develop a dynamical understanding of the flow pathways and their seasonal variability. An approximate theory for the sea surface height anomaly within the Norwegian Sea Gyre interior may be derived by considering a mass balance within a closed *f/H* contour. This approach is similar to that of Nøst and Isachsen (2003) and Isachsen et al., (2003), including the ageostrophic radial velocity forced by the acceleration of the azimuthal velocity. Preliminary analysis indicates that, for seasonal and shorter period forcing, this term is as large as the bottom boundary layer term. Simplifying assumptions allow for analytic solutions that take the form of a forced oscillator where the nondimensional constants make explicit the influence of the environmental parameters on the amplitude and phase of the response. This barotropic theory does not assume that there is no baroclinic shear, only that the response to time-dependent forcing is primarily barotropic, consistent with the findings of Isachsen et al. (2003) and Chafik et al. (2020). The theory also predicts the mass exchange between the gyre and the adjacent boundary currents that are measured by the joint mooring array. For *f/H* contours near the sill depth this provides guidance as to the location and vertical structure of the overflow variability. The amplitude of the exchange predicted by preliminary consideration of the theory is O(0.2-0.4 Sv), similar to the observed seasonal variability in the overflow strength, suggesting that they are coupled. Although very idealized, the theory provides a dynamical framework for the water mass exchange between the gyre interior and the boundary currents/overflow and how it depends on the forcing frequency (Objectives 1 and 2). This in turn will be tested using the observational mooring timeseries from the Iceland-Faroe Ridge and the Faroe Bank Channel sill.

An idealized configuration of the MITgcm (Marshall et al., 1997) will be developed to test the basic predictions from the theory. The domain will include a deep basin and a sill and will be forced with oscillating winds. The gyre/boundary current mass and momentum budgets in the model will be diagnosed and compared to the predictions from the theory. If the leading order balances are different, we will attempt to modify the theory accordingly. The idealized model will then be used to test the parameter dependencies predicted by the theory, including how the amplitude and phase depend on bottom drag, amplitude of wind stress curl, and forcing frequency (Objectives 1 and 2). This will subsequently be used to put the observations in a dynamical context.

The realistic model of Chafik et al. (2020) will be used in two ways. First, forward and backward trajectories from the IFSJ will be constructed for different seasons and years by UFO collaborator L. Chafik (see Section 4). This will identify the sources and fates of the water in the IFSJ and help interpret the observational data (Objective 3). Second, the mass balance within regions of closed *f/H* contours just below the sill depth will be evaluated (by Co-PI M. Spall). This is an important step that will bridge our understanding of the basic physics from the idealized model and theory to the realistic regime represented in the Chafik et al. (2020) model, which includes complex bottom topography, mean currents, buoyancy-forcing, baroclinicity, nonlinearities, and eddy fluxes (Objectives 1 and 2). In the event that any of these physical processes are determined to be important, the theory will be modified to try to include them. For example, a parameterization of baroclinic instability or diapycnal mixing due to buoyancy-forcing may be added to the theory.

4. International collaborations

Besides WHOI, the UFO program will include contributions from six foreign institutions who share an interest in furthering our understanding of the dense water pathways feeding the FBCO. These organizations specialize in research in the Nordic Seas and the subpolar North Atlantic Ocean, and will bring invaluable expertise and considerable resources to our cooperative program. An extensive amount of planning has taken place among the participants to shape the program, including three meetings. The contribution from each group is described below, which highlights the synergistic nature of UFO (refer to Fig. 4a). Some of the components are already funded, while others are in the proposal stage (this is clarified below). See the letters of collaboration from each institution. With such a composite observational system in place, together with the model/theory component, we will be poised to advance our understanding of the inter-connectivity and dynamics of the broad circulation system that supplies the densest water to the North Atlantic Ocean as part of the AMOC.

i. Faroe Marine Research Institute (FAMRI; H. Hátún; K.M.H. Larsen; B. Hansen) As described above, FAMRI will deploy one of the moorings in the NSG Rim (Fig. 4a, blue star) and provide an ADCP as part of the MMP array. In addition to this, FAMRI will occupy their standard hydrographic sections (Fig. 4a, open dark-green circles) four times a year. We note that FAMRI's new research vessel, R/V *Jákup Sverri*, has a hull-mounted ADCP which adds valuable velocity information. During UFO, additional hydrographic stations will be added to the northern section in the vicinity of the IFSJ for better resolution. FAMRI will also occupy another section adjacent to the joint mooring array (Fig. 4a, open light-green circles) on their mooring cruises to the Iceland-Faroe Ridge. The data from these quarterly surveys will aid in the interpretation of both the mooring data and WHOI's broadscale shipboard surveys. FAMRI will also continue to maintain their two FBCO moorings at the sill of the channel, as well as their mooring in the Faroe Current (Fig. 4a). Finally, FAMRI will deploy two moorings at strategic locations on the Iceland-Faroe Ridge to look for evidence of overflow directly across the ridge, which will allow us to further explore links between the different parts of the dense water system. [All of the FAMRI shipboard work is funded, while the moorings are proposed. It is important to note, however, that there is likely in-house funding to deploy the moorings if FAMRI is unsuccessful in obtaining external funds for this.]

ii. University of Bergen, Norway (UiB; I. Fer; K. Våge) As explained above, UiB will occupy a Seaglider transect across the NSG Rim (Fig. 4a, blue line), maintain a mooring in this current along with FAMRI, and provide an ADCP as part of the MMP array. In addition to this, UiB will operate a Seaglider to the northeast of the Faroe-Shetland Channel on the Norwegian continental slope (Fig. 4a, blue polygon). The track was chosen to sample the region where Chafik et al. (2020) suggest that the dense water from the IFSJ retroflects into the Faroe Shetland Channel. The eastern leg of the Seaglider track corresponds to the Svinøy transect, which is sampled four times per year by the Institute of Marine Research in Bergen. Finally, UiB is maintaining a Seaglider in the Iceland Sea and another in the Greenland Sea, which will both be operational during UFO and will provide valuable information on the upstream water mass sources of the FBCO. [All of the UiB contributions are funded except for the Seaglider being used to extend the profiling array, which is proposed to the Research Council of Norway and also to a UiB internal funding call.]

iii. University of Hamburg, Germany (UH; J. Baehr) As detailed above, UH will provide ADCPs, Aquadopps, and MicroCATs as part of the MMP array. The 6 upward-facing long-ranging ADCPs together will augment the array in important ways. First, the coverage (shown by the thick blue lines in Fig. 4b) will enable us to construct hourly vertical sections of velocity in the bottom 500 m of the water column across the main part of the IFSJ (recall that the flow is bottom-intensified, Semper et al., 2020). This will bolster the transport estimate and allow for a more informed interpretation of the high-frequency variability. It will also provide tidal information that, together with the Aquadopps on the two endpoint MMP moorings, can be used to remove the tidal signals at each of the sites. [All of the UH instrumentation is currently in house.]

iv. Marine and Freshwater Institute of Iceland (MFRI; A. Macrander) Four times a year MFRI occupies their standard hydrographic sections around Iceland. These sections were instrumental in the discovery and quantification of the NIJ (e.g., Pickart et al., 2017; Semper et al., 2019), and were also valuable in documenting the IFSJ (Semper et al., 2020). During UFO, extra stations will be added to key sections north of Iceland, and an additional high-resolution transect will be occupied between the two zonal sections east of Iceland (Fig. 4a, open black circles; note that there are additional standard sections north of Iceland outside of the domain of Fig. 4a). This information will be extremely helpful for determining the upstream origin of the IFSJ. MFRI will also maintain their mooring in Denmark Strait, which will provide contemporaneous information on the dense overflow across the western portion of the GSR. [The MFRI mooring and quarterly cruises are funded; the cost of the incremental shiptime required for the additional stations and section is proposed.]

v. NORCE Norwegian Research Center AS (NORCE; E. Jeansson) The contribution from NORCE will consist of geochemical tracer measurements on the two WHOI broadscale hydrographic/velocity cruises. This includes oxygen, nutrients, CFC-12, and SF_6 (see the Data Management Plan for details). These tracers have proved valuable in previous studies investigating the water mass constituents and origins of the dense water approaching the GSR (e.g., Olsson et al., 2005; Jeansson et al., 2008; Jeansson et al., 2017). It will be particularly enlightening to combine these traditional tracers with the sigma-pi distance metric used by Huang et al. (2020), which together will provide a more rigorous assessment of the origins and mixing of the dense water masses as they progress to the FBCO. [The NORCE component is presently proposed to the Research Council of Norway.]

vi. Stockholm University, Sweden (SU; L. Chafik) As explained in Section 3.5, L. Chafik will take the lead on the Lagrangian trajectories used to investigate the sources and fates of the waters in the IFSJ. We will work closely on the design and interpretation of these diagnostics in light of the observational data. Output from this model will also be provided to Co-PI Spall for diagnostic analysis of the mass and momentum budgets to be used to evaluate the theory and idealized model results.

5. Broader Impacts of the Proposed Research

UFO is a collaborative field and model/theory program that will answer a host of pressing open questions regarding the sources of dense water feeding the FBCO. In doing so, we will fundamentally advance our knowledge of the deep limb of the AMOC which is a critical component of the global climate system. Significant effort has been spent in the community over the past 10+ years investigating the mechanisms, forcing, and variability of the AMOC, including the RAPID-MOCHA and OSNAP observing systems in the subtropical and subpolar North Atlantic, respectively. One of the goals of OSNAP is to elucidate the connection between deep water formation (Labrador Sea Water and Nordic Seas deep water) and the AMOC. UFO has direct relevance to this by determining where the densest water is formed in the Nordic Seas, and how this water progresses to the GSR and is modified along the way, including the role of atmospheric forcing. In doing so, we will gain a better understanding of the means by which the warming climate may impact the AMOC.

The proposed project will fund a postdoctoral investigator (2 years) who will work with Pickart on the analysis of the WHOI/UH/UiB/FAMRI mooring and glider data in collaboration with our international collaborators; see the supplementary document entitled “Postdoctoral Mentoring Plan.” The post-doc will also interface with Spall in melding the model with the observations. Two guest graduate students will also be funded (1.5 years each) who will focus, respectively, on the shipboard data from the two hydrographic/velocity surveys, again in conjunction with Pickart, Spall, and the international PIs. As such, both the students and the post-doc will interact with a broad community of researchers studying a wide range of issues associated with the Nordic Seas and subpolar North Atlantic. These interactions will include scheduled PI meetings as well as extended visits to partnering institutions.

The proposed project will have an outreach program that includes a project website and host of activities engaging the public in the fieldwork. Pickart has an established track record of public outreach, with the most recent example being the Iceland-Greenland Seas Project (see Results from Prior NSF Support). The UFO outreach program will be centered around the 2023 cruise, with an aim to produce visually engaging content for daily cross-platform social media posts. This cruise was chosen since the hydrographic/velocity survey will have an exploratory element to it as we seek to determine the upstream origins of the dense water; this makes it particularly well-suited for engaging the general public. Photographer/filmmaker Amanda Kowalski and illustrator Betsy Green will work from aboard the vessel to create social media posts that will draw attention to the science mission as well as broader topics such as the relationship between the AMOC and Earth's climate. Content will include photographs, video shorts (ninety-seconds or less), and illustrations that feature images of the science in action and life aboard the ship. A professional writer will compose daily essays on the cruise that are accompanied by photographs and posted to the project website, such as those written by author Dallas Murphy for the previous study of the dense water pathways feeding Denmark Strait, which resulted in a book (Murphy, 2012). The outreach team will work with a production assistant ashore who will submit the social media and website posts and connect with WHOI communications as well as the other public media outlets and regional high schools' Instagram accounts.

6. Data Management

All of the data resulting from the WHOI fieldwork will be submitted to the Arctic Data Center. In addition, we will maintain a WHOI-based UFO website that will provide public access to all of the WHOI data as well as those collected by our international partners. A detailed description of the data management and dissemination are presented in the supplementary document entitled "Data Management Plan."

7. Results from prior support

R. S. Pickart and M.A. Spall, co-PIs: *Ventilation of Denmark Strait Overflow Water in the Iceland and Greenland Seas (OCE-1558742, $1,121,001, June 2016 – May 2021).*

Intellectual Merit: This project was a collaborative field program and model study with nine different international institutions to investigate wintertime water mass transformation in the western Nordic Seas and the pathways by which this dense water is transported to the Greenland-Scotland Ridge. A two-leg cruise was conducted in Feb-Mar 2018 in coordination with an atmospheric field campaign that consisted of 14 flights. A year-long run of the MITgcm was carried out for the year of the fieldwork. The ocean response to the atmospheric forcing was markedly different in the boundary current region versus the interior of the western Iceland Sea. Over the continental slope, lateral advection and mixing strongly modulated the response to the air-sea heat flux, while in the deep basin the mixed layers were deeper and denser and the response was predominantly dictated by the atmospheric forcing. Eddies spawned from the boundary current played a critical role in the water mass modification, leading to a very heterogeneous mix of water mass products.

Broader Impacts: A PhD student was supported by the project, and numerous graduate students and post-docs participated in the fieldwork. A project website was created and continues to be updated. The field program was featured in the Public Radio International series, *The World*, as well as in the French documentary, *The weather: A race to forecast*, and on the Norwegian Broadcasting Corporation NRK. A feature length documentary entitled *The Alliance* was made and is now being submitted to different film festivals. There were 30 peer-reviewed publications from this grant (denoted by asterisks in the references). The data collected during the fieldwork reside at the project website (Iceland-Greenland Seas Project), and at the Arctic Data Center.