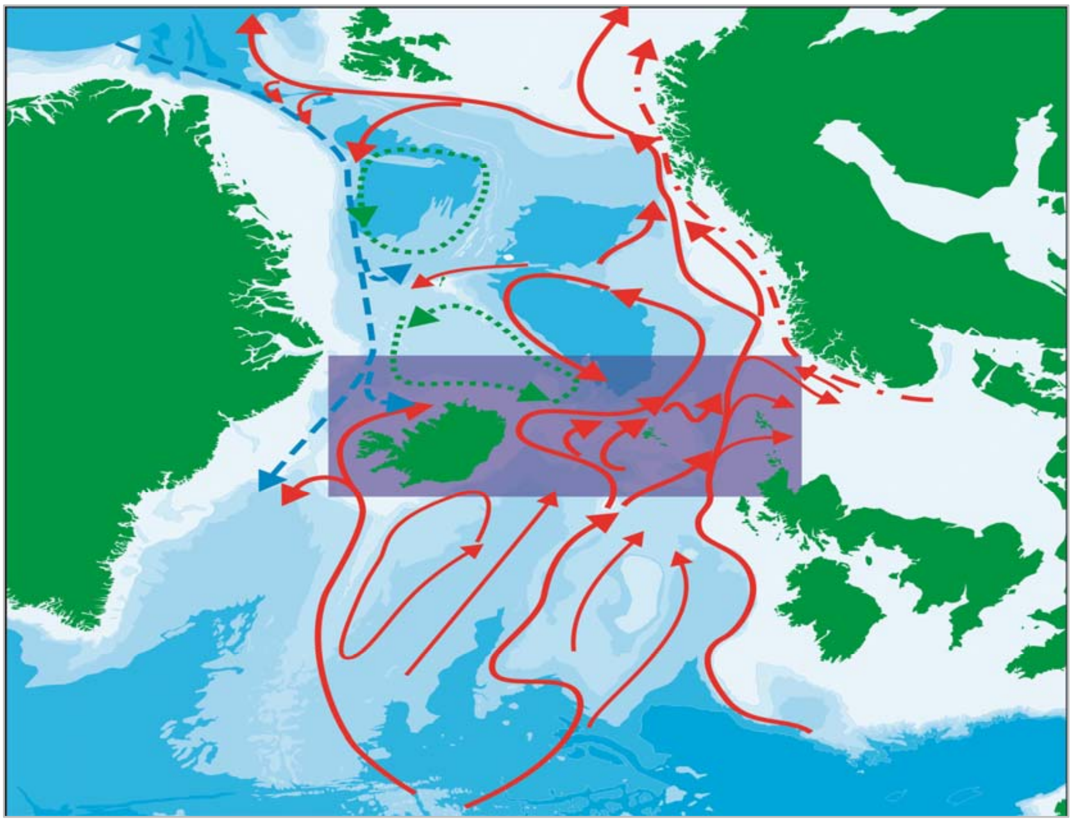
# Optimization of the Greenland-Scotland Ridge inflow arrays



Surface flows in the North Atlantic and Nordic Seas. The box outlines the Greenland-Scotland Ridge inflow area. Red arrows indicate Atlantic water inflow. Credits: Svein Østerhus (NORCE)

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## Summary for publication

Ocean warm and saline Atlantic water (AW) flows northward towards the Arctic. This water crosses the Greenland-Scotland Ridge in three inflow branches:

- the Iceland branch,
- the Faroe branch and
- the Shetland branch.

The first monitoring of these branches was obtained along standard hydrographic sections and in the 1990s these observations were complemented by – at that time the state-of-the-art technology – Acoustic Doppler Current Profilers (ADCPs) that could measure ocean currents directly. For many years the ADCPs were the backbone in transport estimates of the inflowing AW, but in order to get reliable estimates, a high number of moorings were necessary which was costly both in consumables and man-power. Alternative methods were therefore needed. The process to optimise the inflow arrays began several years ago by the integration of Satellite Altimetry data . Over the years, more data have been obtained at the inflow arrays, including new data types, and within Blue-Action analyses have been performed utilizing the available data in order to optimise the monitoring of the inflow arrays both with respect to cost and in order to produce more accurate estimates of AW volume, heat and salt transports. Resulting from the work undertaken in Blue-Action, **the recommendations for future monitoring the three inflow branches are as follows**:

- **Iceland branch**: Combined observations from one or two ADCP moorings (including hydrographic observations at intermediate depth) and four annual hydrographic surveys.
- **Faroe branch**: Combined observations from satellite altimetry, one ADCP mooring, three PIES (Pressure Inverted Echo Sounders), one bottom temperature logger and at least three annual hydrographic surveys.
- **Shetland branch**: A combination of gridded geostrophic surface velocities from satellite altimetry, at least three annual hydrographic cruises along the section and continued ADCP deployments at key sites (such as in the Shetland slope current).

## Work carried out

The Greenland-Scotland Ridge (GSR) observatory covers three branches of Atlantic inflow towards the Arctic: the Iceland, Faroe and Shetland branches (Figure 1). Monitoring of these branches was initiated in the mid-1990s in the Nordic WOCE project and the monitoring has continued with funding mainly from the EU, including the FP7 projects THOR and NACLIM. Adjustments and optimization of the Transport Mooring Arrays (TMA) has been an ongoing process especially within NACLIM, where the work to integrate satellite observations in the calculation of volume fluxes was initiated (Berx et al., 2013; Hansen et al., 2015). Building on the previous projects, we here aim to finalize the optimization process where the aim is both to reduce the TMA running costs, to integrate new data types (e.g. New Earth Observations), while continuing to make reliable estimates of the fluxes. Preliminary estimates of the transport time series can be calculated for the Faroe and Shetland branches using near real time (NRT) satellite altimetry thereby allowing more rapid data availability. Nevertheless, a comparison between NRT and delayed time (DT) data products indicated that the

NRT products have much higher variability than the DT products and it was therefore decided to use the DT products only (Hansen et al, 2020).

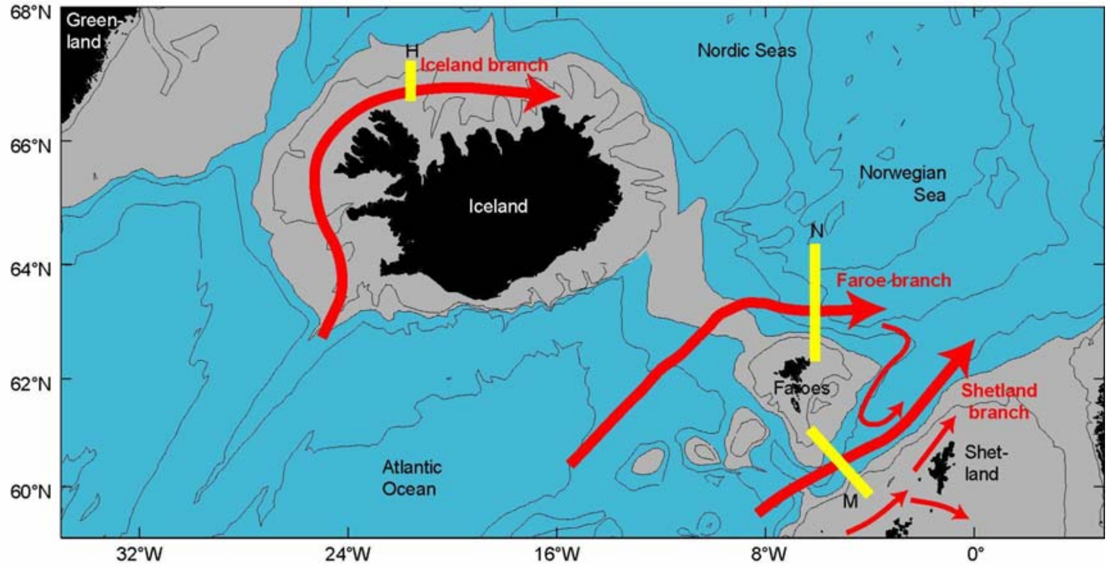

**Figure 1**: The Greenland-Scotland Ridge. Atlantic inflow to the Nordic Seas crosses the ridge in three branches: 1) The Iceland branch monitored at section H, 2) the Faroe Branch monitored at section N and 3) the Shetland Branch monitored at section M (often termed the FIM line). Grey areas are shallower than 500 m. From Østerhus et al. (2019).

Below, the work carried out for each inflow branch is described. Most of the field work has not been funded by Blue-Action, but these observations contribute to the analysis done within Blue-Action.

## Iceland branch

The North Icelandic Irminger Current (NIIC) carries Atlantic water through Denmark Strait into the Iceland Sea. The Atlantic water inflow is highly variable due to mixing with Polar water and wind stress. A hydrographic section with five CTD stations across this inflow branch is taken four times per year (Figure 2). In addition to the seasonal sections, the Atlantic water inflow has been monitored at Hornbanki by moored current meters since 1994, and ADCPs since 2009. The volume flux is determined by integration of the velocity measurements and the mixing ratio of Atlantic and Polar water by applying a mixing scheme to the T/S data provided by Microcats on the moorings (Jónsson and Valdimarsson, 2012).

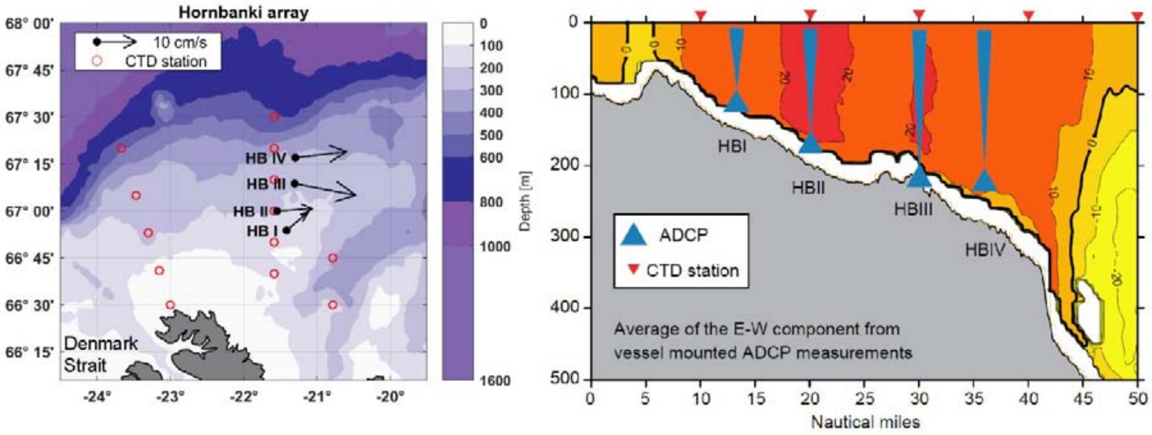

**Figure 2:** Hornbanki array, north of the Westfjords region in Iceland. Left panel: Black dots and arrows denote mooring positions and average current at 70 to 100 m depth in 2010-2018. Red circles denote hydrographic standard stations. Right panel: Average cross-section current observed by vessel-mounted ADCP in the period 2001-2004. Red denotes eastward current, exceeding 20 cm/s where the NIIC is strongest. Yellow denotes westward current and white is no data available; at the shelf edge the North Icelandic Jet is visible. Mooring positions of the Hornbanki array projected on the section marked with blue symbols. Figure from Larsen et al. (2020).

Between one and four moorings (HBI to HBIV) have been deployed (Figure 2). Altimetry was not used for optimization, as Hornbanki is north of the Topex/Poseidon turning latitude, and fairly close to the coast and sea ice, making altimetry less reliable (c.f. Macrander et al., 2014). Instead, it has been investigated how much difference it makes if fewer moorings are used, revealing that a reasonable estimate of the transport can be obtained with HB III (and HB II) alone (MRI). These turned also out to be the safest positions, while at HB I and HB IV moorings were lost due to fishing or icebergs.

Despite these risks, a continuously measuring mooring array is necessary to determine the Atlantic inflow into the Iceland Sea, as transport estimates from seasonal hydrographic sections can be biased due to the high variability of the NIIC even on timescales of a few days. The optimized monitoring system for this inflow branch will therefore combine observations from one or two ADCPs and Microcats as well as four annual CTD surveys to track long-term water mass variations (MRI). At present (as of May, 2020), two moorings (HB II and HB III) are deployed. Both moorings are equipped with an upward-looking 150 kHz ADCP that is sampling current profiles from between 200 m and the surface, as well as two Microcats at ca. 180 m and 80 m depth, respectively, sampling temperature and salinity in the core depth of the Atlantic inflow.

### Faroe branch

The inflow of Atlantic water between Iceland and Faroes is the strongest inflow branch in terms of volume transport (Østerhus et al., 2019) and is monitored by HAV on a section extending northwards from the Faroe shelf. Hydrographic monitoring with regular CTD cruises was initiated in the late 1980s. In the late 1990s, this was complemented by moored ADCPs. This monitoring system was demanding to maintain both in terms of manpower and funding. A study published in 2015 (Hansen et al., 2015) indicated that gridded sea level anomaly (SLA) data from satellite altimetry might be able to replace much of the in situ observations.

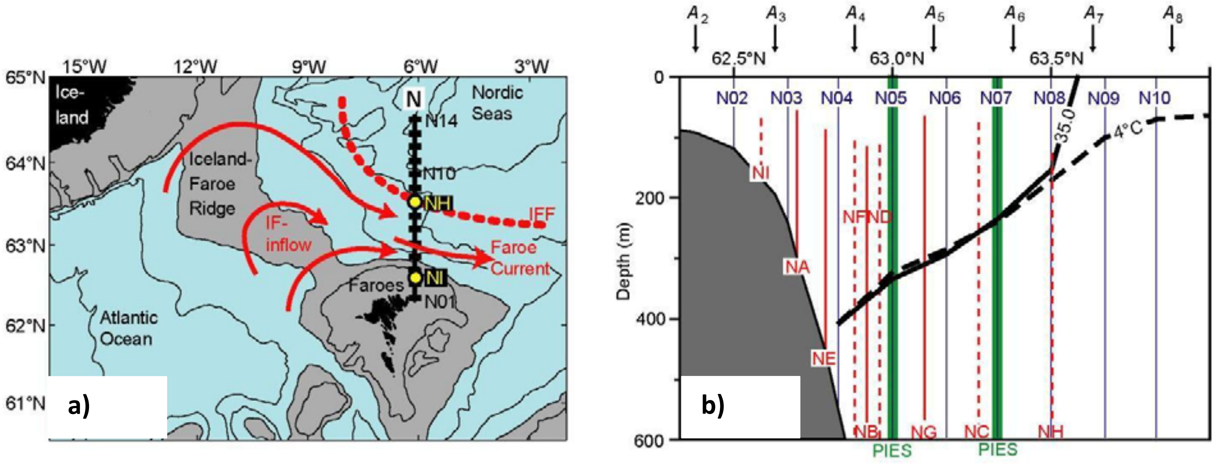

**Figure 3: (a)** The region between Iceland and the Scottish shelf with grey areas shallower than 500m. The Faroe branch (red arrows) enters the Arctic Mediterranean between Iceland and Faroes where it meets colder waters of Arctic origin in the Iceland-Faroe Front (IFF), and flows north of Faroes in the Faroe Current. The black line extending northwards from the Faroe shelf is the N-section with CTD standard stations N01 to N14 indicated by black rectangles. Yellow circles indicate the innermost (NI) and the outermost (NH) ADCP mooring sites on the section. **(b)** The southernmost part of the N-section with bottom topography (grey). CTD standard stations are indicated by blue lines labelled N02 to N10. ADCP profiles are marked by red lines that indicate the typical range with continuous lines indicating the long-term sites (>2700 days of measurement). Thick green lines indicate two PIES deployments. Altimetry grid points $A_2$ to $A_8$ are marked by black arrows and the thick black lines indicate the average depth of the 4 °C isotherm (dashed) and the 35.0 isohaline (continuous) on the section (from Hansen et al., 2015).

In recent years, ADCP observations at two new sites (NI and NH in Figure 3) at the outskirts of the inflow branch have been obtained. Also, PIES (Pressure Inverted Echo Sounders) were deployed in order to get better and continuous estimates of the isotherm separating the Atlantic water and the deeper water masses. These observations have been done within the Danish funded FARMON project and the PIES observations have been done in collaboration with the University of Hamburg. Within Blue-Action and partly within FARMON, a thorough analysis of all the available in-situ data from the section has been performed and combined with altimetry data (including new earth observations from Jason-3 and Sentinel-3A). This analysis is documented in a technical report on monitoring the velocity structure (Hansen et al., 2019a) and two reports on monitoring the hydrographic structure (Hansen et al., 2019b; Hansen et al., 2020) of the Faroe Current. Details on the results and recommended new monitoring system are given in Main results achieved.

### Shetland branch

The inflow of Atlantic water in the Faroe-Shetland Channel (FSC) is second in terms of volume, temperature (also referred to as heat transport relative to 0°C) and salt transport (Østerhus et al., 2019). Hydrographic monitoring using bottle measurements at discrete depths and stations on an annual basis was initiated in the early 1890s, and was expanded by MSS and HAV in the mid-1990s to more surveys throughout the year using CTDs to collect continuous profiles. This coincided with the establishment of a transport mooring array to collect direct measurements of currents in the mid-1990s (Figure 4). In recent years, the increasing costs have significantly reduced the extent of the in situ monitoring system, and in most recent years current meter deployments have focused on collecting data to provide context to other projects.

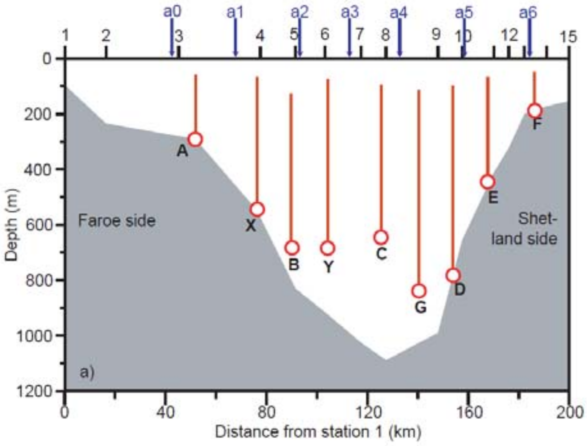

**Figure 4:** Overview of monitoring observations across the Faroe-Shetland Channel (along section M in Figure 1) showing standard hydrographic stations labelled 1 to 15 and altimetry grid points a0 to a6 on top. Red circles indicated moored ADCPs with the ranges indicated by vertical red lines.

As part of this Blue-Action deliverable, MSS and SAMS have further investigated integration of satellite altimetry with hydrographic surveys to produce time series of volume, temperature and salt transport of the Atlantic inflow in the FSC.

# Main results achieved

A synthesis of Arctic Mediterranean exchanges, including the GSR inflow branches is provided in Østerhus et al. (2019). They find that for the observational period spanning two decades there is good agreement between the average inflows and outflows and further they argue that the inflow branches (and the two main overflow branches) are likely to give a good representation of the long-term changes. For the given observational period, the inflows did not weaken, which is in contrast to reported weakening of the Atlantic Meridional Overturning Circulation (AMOC) at lower latitudes (Smeed et al., 2018). Nevertheless, this does not exclude future changes in the Atlantic inflow branches (Larsen et al, 2018) and it is therefore recommended that the monitoring systems are maintained and possibly expanded (Østerhus et al., 2019).

**Here we present the main results and recommendations for the future monitoring of the three inflow branches of the GSR-observatory.**

### Iceland branch

In addition to optimization of the Hornbanki mooring array, work has been done in combining satellite altimetry, hydrography and shipboard ADCP data to investigate the along-stream, seasonal and interannual variability of the North Icelandic Irminger Current (NIIC) and East Icelandic Current (EIC) (Casanova-Masjoan et al., 2020, submitted). In this study, absolute geostrophic velocities were calculated from hydrographic data from all seasonal sections in the period 1993 to 2017, and altimetry-based absolute Sea Surface Height. Lowered ADCP/mooring data were used as ground truth where available. Some of the results of the paper are mentioned below. It is shown that some of the water in the NIIC is recirculated back towards Denmark Strait prior to reaching the Kolbeinsey Ridge, east of the monitoring section. After crossing the Kolbeinsey Ridge the two currents merge and then flow as a single entity to the east. The NIIC has become warmer, saltier and its transport increased over the period 1993-2017. The dynamics of the current system is studied on seasonal and interannual time scales and relations to climate indices such as Greenland Blocking Index, NAO and AMO were investigated.

**Recommendations for future monitoring of the Iceland branch:**
The optimized monitoring system for this inflow branch will build on and combine observations from:

- Two upward-looking ADCP moorings (HB II and/or HB III) sampling current profiles from between 200 m and the surface, each including two Microcats at intermediate depths sampling temperature and salinity in the core depth of the Atlantic inflow.
- Four annual CTD surveys to track long-term water mass variations.

**Faroe branch**

Monitoring the Faroe branch involves observing the variations of the velocity field on the monitoring section (section N in Figure 1), but also the variations of the temperature as well as the salinity fields. This is required to derive heat (relative to some reference temperature) and salt/freshwater transports, but it is also required to distinguish the Atlantic water on the section from other water masses of Arctic origin. Optimizing this effort involves two main tasks:

- designing a low-cost high-quality system for future monitoring, and
- combining all available information to extend high-quality transport time series as far back in time as possible to provide a baseline for future variations.

**To do this, a number of questions had to be addressed**. Some of these questions had been partially answered in previous studies, but they have all been completed within the Blue-Action project, as detailed below.
Most of these results have been detailed in three technical reports (Hansen et al., 2019a; 2019b; 2020).

**Question: How accurately can the temporal variations of surface velocity in the Faroe Current be derived from Sea Level Anomaly (SLA) data?** To answer this question, velocities from the various ADCP sites have been correlated with differences between SLA-values at neighbouring grid points from a line of altimetry points along the monitoring section (Figure 3b). Since the transport time series are produced at monthly time scales, the values were averaged over 28 days before correlation. The ADCPs do not profile all the way to the surface, but the velocity variations of the Faroe Current are highly barotropic and geostrophic (dynamic) calculations of velocity shear from CTD surveys can also help to extend the ADCP profiles all the way to the surface as documented in a technical report (Hansen et al., 2019a). When this set of 28-day averaged ADCP derived surface velocities was compared with the SLA values, the initial result was not encouraging (Table 4a in Hansen et al., 2019a). This is in contrast to results from two other experiments in the region with high correlations between ADCP measurements and SLA values (Hansen et al., 2017; Hansen et al., 2018). These two experiments involved narrow currents that are locked by steep topography, whereas the Faroe Current is broad and meandering. Surface velocities derived from sea level differences across an altimetry interval represent the velocity horizontally averaged across the interval. ADCPs, on the other hand, measure the velocity at one geographical location. This indicates that the SLA-derived velocity variations are more representative than indicated by the initial SLA-ADCP comparison and this was confirmed by combining the surface velocities measured by four ADCPs covering the core of the current into one time series. The correlation coefficient between 28-day averaged values of this time series with SLA-differences across the current was 0.86 ($p<0.001$) (Hansen et al., 2019a). The answer to this question is therefore: ***Sea Level Anomaly (SLA) data from satellite altimetry can provide accurate time series of horizontally averaged surface velocity variations on monthly time scales and a dense array of ADCPs would be required to provide better estimates.***

**Question: How can SLA-derived surface velocity anomalies be converted into absolute surface velocities?** Since the SLA-values are anomalies, the surface velocities derived from them are also anomalies and a constant "Altimetric offset" has to be determined for each altimetry interval to convert them to absolute velocities. These values may be derived for each interval from information on the geoid and Mean Dynamic Topography, but Hansen et al. (2015) noted that this would give surface velocities that are too smooth horizontally, which would increase velocities in regions with a shallow Atlantic layer and reduce them where the layer is deep. Instead, Hansen et al. (2015) used extended ADCP profiles and geostrophic (dynamic) velocity shear from CTD cruises to determine $U_k^0$ values. These calculations have been updated within Blue-Action by Hansen et al. (2019a), using also the new in situ observations (Figure 5). So the answer to this question is:

***The Mean Dynamic Topography from AVISO is too smooth to give realistic absolute surface velocities for the Faroe Current, but the in situ observations allow calibration of the SLA values to give accurate absolute velocities.***

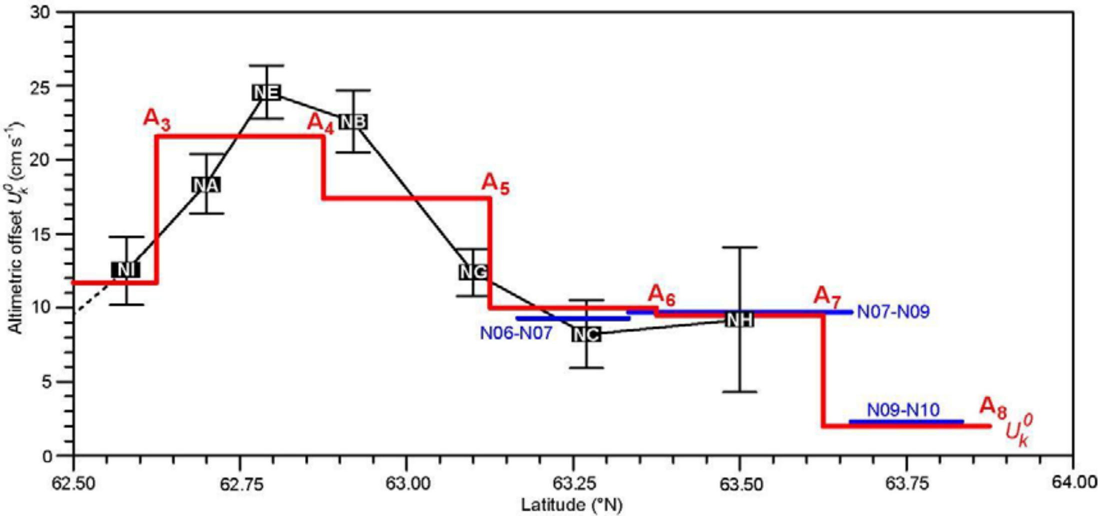

**Figure 5:** The red line indicates the values of the "Altimetric offset" ($U_k^0$), which is needed to convert the SLA difference ($\Delta H_k(t)$) across the interval $A_k$-$A_{k+1}$ to absolute velocity: $U_k(t) = \frac{g}{f \cdot L} \cdot \Delta H_k(t) + U_k^0$. Black rectangles with ADCP site names indicate values derived from individual ADCP sites with error bars indicating 95% confidence intervals. Blue lines indicate $U_k^0$ values derived from CTD data and measurements of deep currents. From Hansen et al. (2019a).

**Question: How well do the altimetry-derived surface velocities represent sub-surface velocities and vertically integrated velocities?** A priori, sea level tilt and altimetry are only related to the velocity at the surface; not at depth. As mentioned, the velocity variations in the Faroe Current are, however, highly barotropic, which means that the eastward velocity at a given depth within the Atlantic layer is close to being proportional to the eastward surface velocity. The vertical integral of the eastward velocity – i.e. transport – will therefore also be almost proportional to the eastward surface velocity. The validity of this claim is documented in Table 1, which answers this question: ***Velocity profiles from ADCP measurements show that the vertical integral of velocity down to a given depth is almost proportional to the surface velocity so that volume transport above a given level may be determined from the surface velocity.***

**Table 1:** Correlation coefficients between eastward surface velocity and integrated velocity down to the average depth of the Atlantic layer ($R_A$) for seven ADCP sites, and down to 600 m depth for the four deep sites ($R_D$). From Hansen et al. (2019a).

| Site: | NI | NA | NE | NB | NG | NC | NH |
|---|---|---|---|---|---|---|---|
| $R_A$: | 0.969 | 0.898 | 0.973 | 0.986 | 0.988 | 0.989 | 0.998 |
| $R_D$: |  |  |  | 0.950 | 0.974 | 0.960 | 0.970 |

Combining the answers to the three questions posed above, it may be concluded that: ***Once calibrated by in situ observations, satellite altimetry appears to provide a more accurate description of the variations of the velocity field on monthly time scales than even a relatively dense array of moorings.*** In addition to this, it is necessary to monitor and describe the hydrographic fields and to determine the variations of the Atlantic water extent on the section. This again raises several questions that have been addressed within Blue-Action.

**Question: Can PIES be used to monitor the Atlantic water extent on the monitoring section?** Over most of the section, this involves monitoring the depth of the 4°C-isotherm, which is used as the Atlantic water boundary towards the deep waters (Hansen et al., 2015). The 4°C-isotherm exhibits large and rapid depth variations, for which the CTD profiles only produce snapshots whereas PIES produce continuous time series throughout the deployment period. In addition to pressure, PIES measure the two-way travel time between the sound transducer of the PIES (which should not move) and surface. Both of these parameters vary with a variable sea level, but also with variations in the temperature and salinity profiles that affect sound velocity. To check the potential for utilizing this, all the CTD profiles from two standard stations on the section were analyzed and the observed 4°C-isotherm depth plotted against calculated (two-way) travel time (Figure 6).

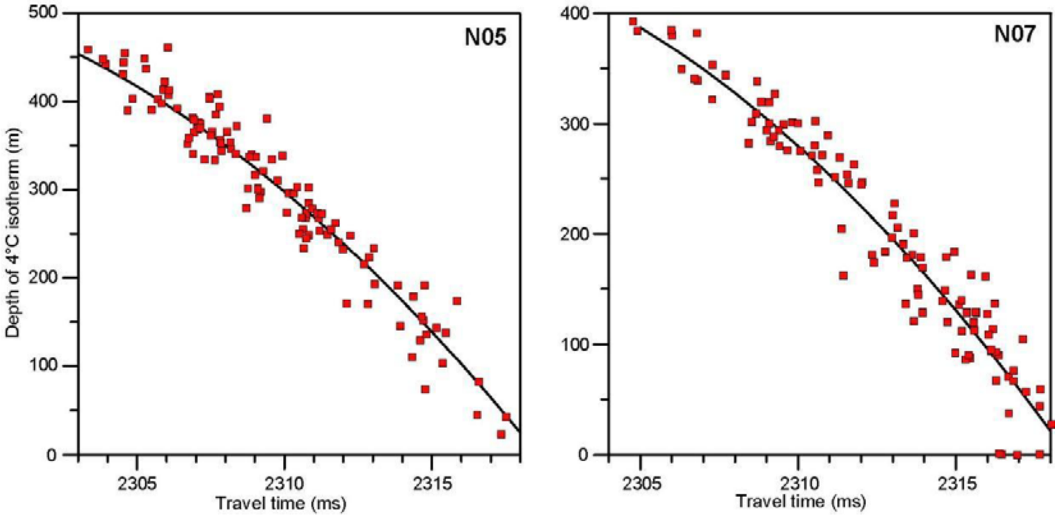

**Figure 6:** Depth of the 4°C-isotherm plotted against calculated travel time for standard stations N05 and N07 assuming a bottom depth of 1695 m and a fixed sea surface. Each red square represents a CTD profile (112 profiles for N05 and 105 for N07). Continuous lines indicate second order polynomial fits. For N07, three occasions with surface temperature < 4°C (i.e., no isotherm in the water column) are included with isotherm depth set to zero. Adapted from Hansen et al. (2020).

The relationships in Figure 6 look encouraging and a PIES was deployed at each of the two stations in 2017 and recovered in 2019. A preliminary analysis of the data was positive and led to the decision to seek funding for three long-term PIES moorings in the new monitoring system (Hansen et al., 2019b). After satellite altimetry had been updated for most of the PIES period, a more complete analysis produced a continuous time series of 4°C isotherm depth for the two stations. CTD profiles obtained during the PIES deployment period were used to calibrate the PIES travel time measurements (requires highly accurate depth) and verify a high quality of the isotherm depth values from the PIES. The average (numerical) difference between the two methods was less than 25 m for both stations and an appreciable fraction of that difference derives from uncertainty in the CTD-derived values due to rapid depth variations (Hansen et al., 2020). Thus: ***Pressure Inverted Echo Sounders (PIES) can provide accurate time series for the deep boundary of the Atlantic layer along most of the monitoring section.***

**Question: How to monitor the Atlantic water extent over the Faroe slope?** The slope region is where the Atlantic layer reaches the largest depth and highest velocities and therefore especially important for transport calculations. A PIES deployed on the slope would, however, be vulnerable to the intensive fisheries. Another option is to monitor the bottom temperature at a site in this region (site NE in Figure 3b). Combining this parameter with altimetry data can explain 66% of the variance in 4°C-isotherm depth at the nearby standard station N04 (Figure 3b) as observed by CTD (Hansen et al., 2020). A newly developed system for monitoring the bottom temperature at NE with acoustic data transmission (Figure 7a) stopped delivering data already after one year. A second system containing four self-contained LoTUS buoys in a protective frame (Figure 7b) was deployed at site NE in 2018. The buoys, which log bottom temperature, were programmed to be released at annual intervals. The first of these buoys should have surfaced and transmitted data in June 2019, but no data were received. A similar system deployed in the Faroe Bank Channel has, however, delivered data. All the buoys store temperature data from the time of deployment and the remaining three buoys are planned to surface in June 2020, 2021, and 2022. It is therefore too early yet to tell how successful this attempt to monitor the depth of the Atlantic layer in the slope region will be.

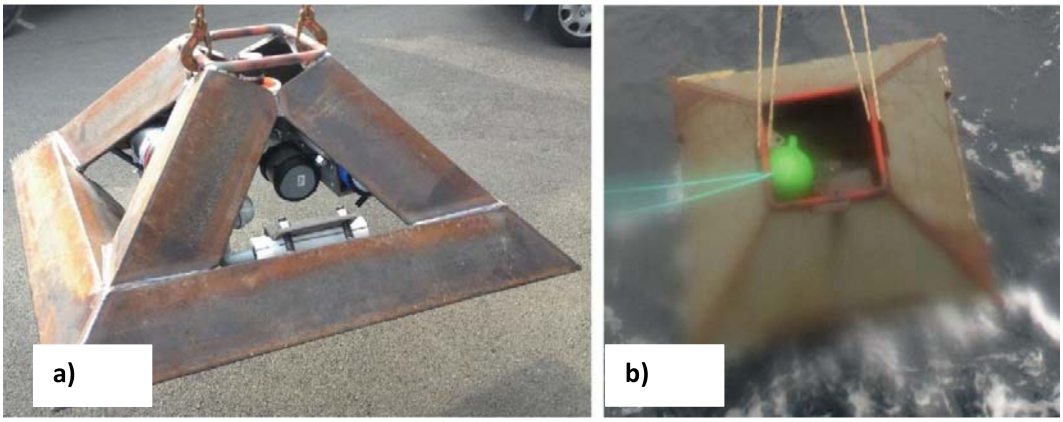

**Figure 7:** Two different types of instrument packages developed by HAV to monitor bottom temperature in heavily fished areas, both of them with instrumentation continuously logging temperature inside protective frames. Data recovery either with acoustic upload to research vessel **(a)** or with timed release of up to four self-contained LoTUS buoys (green in photo) that transmit data after surfacing **(b)**.

**Question: How can the available observational data be combined to extend transport time series for the Faroe branch back in time?** With altimetry giving the velocity field back to its start in 1993, the problem is reduced to determining variations of the hydrographic fields. The long-term variations of Atlantic water temperature and salinity are adequately described by the data set of regular CTD observations, extending back to the late 1980s. The main problem is therefore to determine the variations in Atlantic water extent back in time. Fortunately, there is an almost instantaneous geostrophic adjustment between sea level height and isopycnal (i.e., also isothermal) depth, which was used to simulate Atlantic water extent by Hansen et al. (2015). Within Blue-Action, a re-analysis of the complete in situ dataset (including additional CTD profiles and the PIES data from 2017-2019) has refined and completed the simulation algorithms (Hansen et al., 2020). The simulation algorithms are mainly based on the snapshot CTD observations and include the effects of short-term disturbances such as internal waves and meso-scale features, whereas the transport time series are monthly averages. To see the effect of this, Hansen et al. (2020) compared simulated monthly (28-day) averaged Atlantic layer depth at stations N05 and N07 (Figure 3b) with the monthly averaged observed depth measured by the PIES at these two sites in 2017-2019 with a remarkable result: At N05, the simulated depth explained 62% of the variance in the depth as observed by CTD, but when averaged over 28 days, the same algorithm explained 77% of the 28-day averaged depth observed by the PIES. At N07, similarly, the explanatory power increased from 66% to 79%. This rather unexpected result will have to be further tested by more comprehensive observations but so far, it indicates that ***the simulation algorithms for Atlantic water extent are much more accurate when used to simulate monthly averages than indicated by comparison with the CTD data set from which they were developed.***

**Recommendations for future monitoring of the Faroe branch:**
As new data become available, the new monitoring system will undoubtedly require modifications, but its basic structure is built on five components, planned to be implemented in 2020 (Figure 8):

- Satellite altimetry along 6.125°W longitude to provide SLA data, from which the velocity field is determined and to help monitoring the Atlantic water extent along the section.
- One ADCP at site NB to serve as backup, if major changes to the velocity field should disrupt the established relationships between altimetry and velocity field.
- Three PIES deployed on the bottom at stations N05, N07, and N08 to monitor the depth of the Atlantic layer at these stations and at N06 by interpolation. Each PIES will be moored for several years and data uploaded regularly to research vessel.
- One bottom temperature logger deployed on the bottom in a protective frame at site NE. The presently installed system (Figure 7b) is planned to remain operational until June 2022. This system is developmental and may need re-assessment in future.

  Regular (at least three times a year) CTD cruises along the section. These cruises – which also include other (e.g., plankton) observations – will provide data on long-term variations of the Atlantic water temperature and salinity and update the hydrographic data set to allow continuous refinement of algorithms.

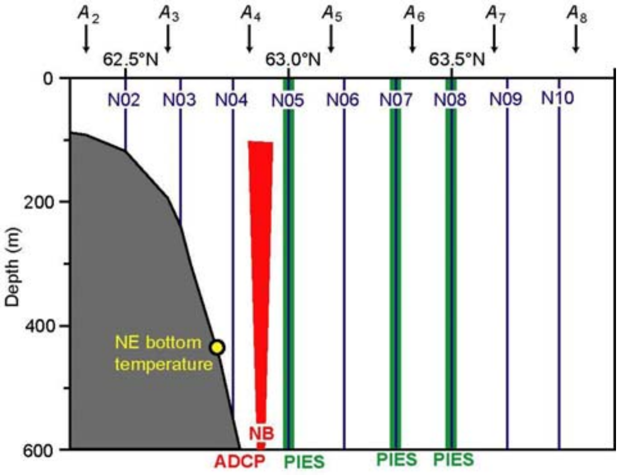

**Figure 8**: The planned new monitoring system for the Faroe branch of Atlantic inflow to be implemented in 2020.

## Shetland branch

The circulation of Atlantic water in the Faroe-Shetland Channel (FSC) is complex as the Atlantic water enters from both ends of the channel (Figure 9). The main transport pathway from the south-west consists mainly of the European Slope Current transporting warm, saline waters along the continental shelf edge (North Atlantic Water). Much of the surface waters in the FSC are, however, slightly less saline and warm (Modified North Atlantic Water), and originate from either further west in the Atlantic basin, or are part of the recirculation of waters from the north-east entrance to the FSC (Hansen et al., 2017). The net volume transport of AW in the FSC is on average 2.7 Sv, of which approx. 80-90% is estimated to be contained within the slope current (Berx et al., 2013; McKenna et al., 2016).

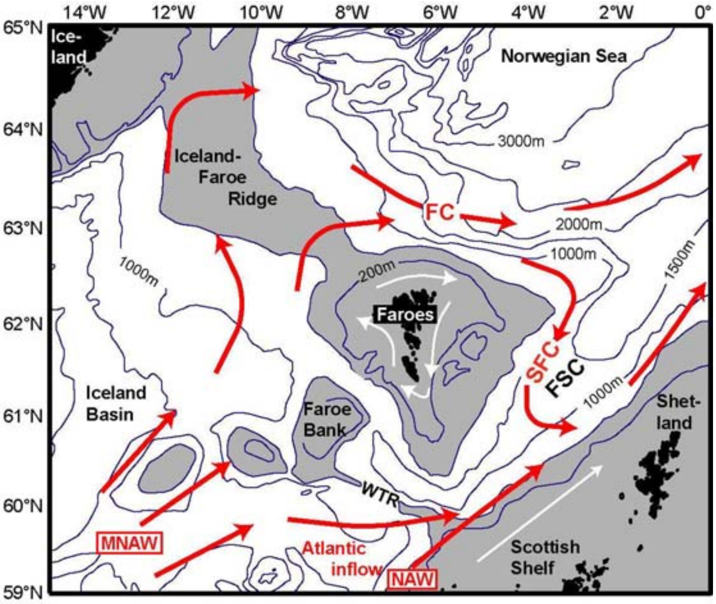

**Figure 9**: Schematic circulation and bathymetry of the Faroe-Shetland Channel (adapted from Hansen et al., 2017). Grey areas are shallower than 500 m. Arrows indicate flows of warm Atlantic inflow as North Atlantic Water (NAW) and as Modified North Atlantic Water (MNAW) in the upper layers off the shelves (red arrows), and shelf water (white arrows). FSC, Faroe–Shetland Channel; WTR, Wyville Thomson Ridge; FC, Faroe Current; SFC, Southern Faroe Current.

Berx et al. (2013) previously showed that satellite altimetry could be used to estimate the monthly average of Atlantic water volume transport using two altimeter grid points on either end of the Fair Isle-Munken hydrographic section (FIM section, Figure 1). This technique provided a continuous time series of the volume transport of Atlantic water in the Shetland branch since satellite altimetry began. However, it could not provide the same for the heat and salt transports. In Blue-Action, work was undertaken to establish whether a combination of satellite altimetry and hydrographic surveys could fill this gap (Walicka, 2018).

**Geostrophic Volume Transport:** For each hydrographic survey, geostrophic shear was calculated between station pairs using the Thermodynamic Equation of Seawater – 2010 (TEOS-10). To obtain absolute geostrophic velocities, these were then referenced at the sea surface to the weekly averaged sea surface geostrophic velocities calculated from the gridded sea surface geostrophic velocities from AVISO satellite altimetry. Transports were calculated between station 3 on the Faroese side of the FSC and station 15 on the Shetland side (i.e. the same representative area of the FSC cross-section as Berx et al.; 2013).

As the velocity shear between station pairs is calculated only to the deepest common depth, a significant portion of transport can be missed where the bathymetry slopes steeply (such as the Faroese and Shetland shelf edges of the FSC). This has been addressed in the calculations by including the transport in these bottom triangles by assuming the flow through these triangles equals that of the lowest common depth. This is likely a conservative estimate due to the flow in the deepest parts of the channel being bottom intensified.

The analysis of the mapping error provided by AVISO suggests that this is relatively high, and even of the order of the surface geostrophic velocities on the Shetland slope of the FSC. However, comparison with the moored

ADCPs across the FSC allows for an independent estimate of the velocity error, which suggests that this mapping error is an overestimate, and the velocity error is nearer to 0.10 m s$^{-1}$.

The average net AW volume transport (defined as warmer than 5°C, Berx et al., 2013) across the FIM section (Figure 1) was 2.69 ± 1.65 Sv (mean ± standard deviation). Figure 10 shows the time series of the volume transport. The variability is large, but some seasonality can be seen. In agreement with Berx et al. (2013), net AW volume transport is largest in winter months (November-February), and smallest in summer (July-August). However, this signal is relatively weak. Analysis of the time series shows the net AW volume transport has been relatively stable.

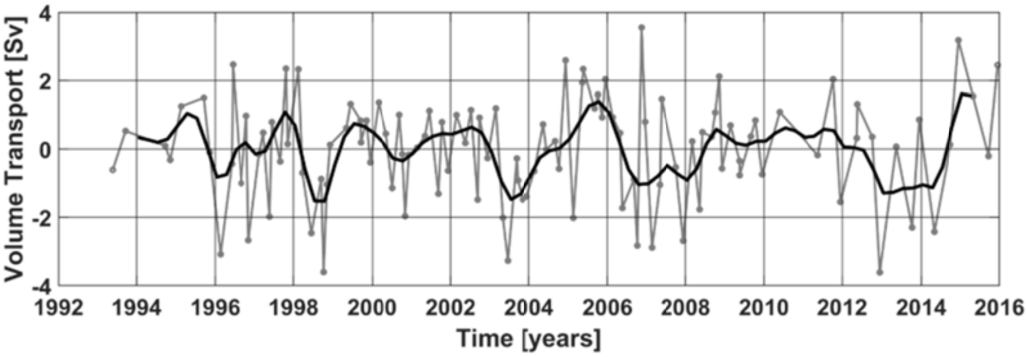

**Figure 10:** Volume transport (Sv) of Atlantic Water (warmer than 5 °C) through the FIM section in the FSC: black circles with thin line are observed geostrophic transport referenced to satellite altimetry geostrophic surface velocities, bold line is a 15-month low pass filter.

**Temperature and salt transport time series:** The temperature transport has been calculated relative to 0°C. This is a measure of the heat transported by the AW inflow, but reduced by that of the deep overflow (its typical temperature is around 0°C). The salt transport has been defined as the amount of salt carried by the current through a section. The average net temperature transport relative to 0 °C through the FSC to the Nordic Seas equals 96.07 ± 55 TW. The average net salt transport transferred to the north was 98.28 ± 60 x 10$^{6}$ kg s$^{-1}$.

The variability of the temperature and salt transport by the Atlantic inflow are strongly influenced by the volume transport.

**Transport Weighted Temperature and Salinity:** The Transport Weighted Temperature (TWT) and Transport Weighted Salinity (TWS) are the average temperature and salinity scaled by the volume transport across the section. In contrast to a straightforward section average, the transport weighted averages are more representative as those locations where most of the transport occurs also carry the most weight in the averaging.

When seasonality is removed, the TWT and TWS show some indication of warming and becoming more saline, there is no statistically significant trend. However, inter-annual variability is in agreement with those observed elsewhere in the North Atlantic.

**Comparison to Viking20 model data:** Outputs from the Viking20 numerical model were used to investigate whether it is suitable to use geostrophic velocities from satellite altimetry to reference the geostrophic shear from hydrographic sections. Results showed good agreement with the observations, although the deep overflow currents had a much higher variability than expected. By smoothing the Viking20 sea surface height (using a similar process used in the satellite altimetry data processing) this increased variability in the deep overflow waters of the FSC was reproduced, suggesting this is an artefact of the method. Further work is needed to investigate the dynamics behind this. The use of geostrophic velocities calculated from a smoothed Sea Surface Height in the geostrophic calculations does not strongly affect the AW volume transport (i.e. the layer warmer than 5 °C). This indicates that the AW volume transport calculated by combining the hydrographic data with sea surface geostrophic velocities measured by satellite altimetry can be used to calculate AW transport in the FSC successfully.

**Recommendations for future monitoring of the Shetland branch**

The monitoring system of the volume, temperature (as heat relative to 0°C) and salt transport of Atlantic water in the FSC will continue to evolve as technological improvements are made and further analyses of the historic time series are explored. In its current structure, the recommended monitoring system includes:

- Gridded geostrophic surface velocities from satellite altimetry along the section.
- Regular (at least three times a year) hydrographic cruises along the section. These cruises – which also include other (e.g. biogeochemistry) observations – will provide data on long-term variations of the Atlantic water temperature and salinity and update the hydrographic data set to allow continuous refinement of algorithms.
- Continued ADCP deployments at key sites (such as in the Shetland slope current) to ensure data availability to verify methods as methods continue to evolve and improve.

A number of initiatives are ongoing to investigate the incorporation of other datasets (such as the Norröna ferry vessel mounted ADCP) and new technologies (such as PIES deployed in 2019). Further adjustments of the method may be reasonably expected depending on outcomes of these analyses.

## Progress beyond the state of the art

- The work done in this deliverable has led to an optimization of the GSR Transport Mooring Arrays and
- a future recommendation is provided such that the Transport Mooring Arrays are “fit for purpose” and sustainable to monitor the important inflows towards the Arctic in the years to come.

## Impact

### How has this work contributed to the expected impacts of Blue-Action?

The work done in this deliverable has improved the uptake of measurements from satellites, including uptake of data from Jason-3 and Sentinel 3A, by combining satellite data with in-situ observations from the Greenland-Scotland Ridge inflow arrays. At the Faroe branch, Pressure Inverted Echo Sounder data have also been included, which is new for this branch. The optimized data products include improved estimates of e.g. ocean heat transport towards the Arctic and are available on-line for the modelling community for use in model assessments etc.

Based on the new algorithms, time series of transport-averaged temperature and salinity have been included into the new time series for the Faroe Current, allowing calculation of heat, salt, and freshwater transport time series to be generated for any given reference temperatures and salinity back to January 1993.

### Impact on the business sector

The technical development of trawl-proof bottom temperature loggers suitable for deployment in heavily fished areas was made in collaboration with Lotussensing (www.lotussensing.com), who provided pop-up LoTUS buoys and Nomatek Ltd. (https://www.nomatek.fo/english-summary/) who designed a trawl-proof frame for the buoys.

## Lessons learned and Links built

- Volume and heat transport in Atlantic inflow to the Nordic Seas has been made available for analysis and model comparison in D2.1 and D2.5.
- The GSR observatory is linked to OceanSITES via H2020 project AtlantOS, and the volume transport time series are available at the OceanSITES webpage (http://www.oceansites.org/tma/gsr.html).
- The PI's of the GSR observatories have a strong link to the Arctic-Subarctic Ocean Fluxes program (https://asof.awi.de/).

## Contribution to the top level objectives of Blue-Action

With this deliverable, we contribute to the achievement of the following objectives of the project:

- **Objective 2 Enhancing the predictive capacity beyond seasons in the Arctic and the Northern Hemisphere**
- by delivering optimised transport estimates for model performance assessments.
- **Objective 5 Optimizing observational systems for predictions** by analyzing and integrating a range of in-situ and satellite observational data from the Greenland-Scotland Ridge inflow arrays thereby producing more accurate data products that can be used by the modelling community. New long-term instrumentation (PIES), which also allows more frequent acoustical data upload, is planned to be added to the Faroe branch TMA. Technical development of a bottom temperature logger suitable for deployment in heavily fished areas has been performed and is being tested. Altogether this increases the sustainability of the TMAs and provides sustainable updates of the data products for use by prediction systems.
- **Objective 6 Reducing and evaluating the uncertainty in prediction systems**: improvements in initialisation of prediction systems are possible with better and more real-time observations.

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Berx, B., Hansen, B., Østerhus, S., Larsen, K. M., Sherwin, T., and Jochumsen, K. (2013) Combining in situ measurements and altimetry to estimate volume, heat and salt transport variability through the Faroe–Shetland Channel, Ocean Sci., 9, 639–654, https://doi.org/10.5194/os-9-639-2013.

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Walicka, K. (2018). Impacts of Basin-scale Forcing on the Circulation of the Faroe-Shetland Channel. PhD Thesis, University of Aberdeen

# Dissemination and exploitation of Blue-Action results

## Dissemination activities

The main dissemination activities linked to this deliverable are listed here below.

| Type of dissemination activity | Name of the scientist (institution), title of the presentation, event | Name of the event | Place and date of the event | Type of Audience | Audience (estimated) | Link to Zenodo upload |
|---|---|---|---|---|---|---|
| Other (technical report) | Hansen, B., Larsen, K.M.H., Hátún, H., Østerhus, S., Atlantic water extent on the Faroe Current monitoring section. Havstovan Technical Report Nr.: 20-03. | | | Scientific Community (higher education, Research), Policymakers | | http://www.hav.fo/PDF/Ritgerdir/2020/TechRep2003.pdf |
| Other (poster) | Karin Margretha H. Larsen (HAV), Bogi Hansen (HAV), Svein Østerhus (NORCE), Steingrímur Jónsson (MRI), Andreas Macrander (MRI), Barbara Berx (MSS), Berit Rabe (MSS). Poster T-2020-248-7, Title: “Optimizing | Arctic Observing Summit 2020 | Held online, 30. March – 2. April 2020. | Scientific Community (higher education, Research) | 20 | https://arctic.ucalgary.ca/sites/default/files/webform/Jonsson_S_Optimizing%20monitoring%20of%20ocean%20fluxes.pdf |

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| | monitoring of volume, heat, and salt transport across the Greenland-Scotland Ridge towards the Arctic" | | | | | |
| Other (technical report) | Hansen, B., Larsen, K. M. H., Hátún, H., Jochumsen, K. & Østerhus, S. 2019b. Monitoring the hydrographic structure of the Faroe Current. Havstovan Technical Report Nr.: 19-02. | | | Scientific Community (higher education, Research), Policymakers | | http://www.hav.fo/PDF/Ritgerdir/2019/TechRep1902.pdf |
| Other (technical report) | Hansen, B., Larsen, K. M. H., Hátún, H. 2019a. Monitoring the velocity structure of the Faroe Current. Havstovan Technical Report Nr.: 19-01 | | | Scientific Community (higher education, Research), Policymakers | | http://www.hav.fo/PDF/Ritgerdir/2019/TechRep1901.pdf |
| Participation to a workshop | • Bogi Hansen (HAV). Title: "Combining satellite altimetry and in situ observations to monitor transports of volume, heat, and salt in the Faroe Current"<br>• Bee Berx (MSS). Title: "Variability of the Atlantic Water inflow to the Nordic Seas via the Faroe-Shetland Channel" | ASOF ISSG meeting 2019 | Copenhagen (DK), 24-26 April 2019 | Scientific Community (higher education, Research) | 50 | https://doi.org/10.5281/zenodo.2669417 |
| Participation to a workshop | Bogi Hansen (HAV). Title: "The Arctic Mediterranean component of AMOC did NOT weaken during the last two decades" | AMAP workshop | Copenhagen (DK), 6-8 November 2018 | Scientific Community (higher education, Research), policymakers | 43 | https://doi.org/10.5281/zenodo.2454096 |
| Participation to a workshop | Karin Margretha H. Larsen (HAV): Title: "GSR TMAs monitored by | ASOF ISSG meeting 2018 | Bergen (Norway), 22-23 October | Scientific Community (higher education, | 25 | https://doi.org/10.5281/zenodo.2454571 |

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| | Havstovan" | | 2018 | Research) | | |
| Others (poster) | Karin Margretha H. Larsen (HAV), Poster HE24C-289, Monitoring One of the Tipping Points of the AMOC | AGU Ocean Sciences 2018 | Portland (US), 11-16 February 2018 | Scientific Community (higher education, Research) | >500 | https://doi.org/10.5281/zenodo.1188871 |
| Non-scientific and non-peer reviewed publications popularised publications | Berx, B., Cottier, F., Cunningham, S., Gallego, A., Holliday, N.P., Hopkins, J., Inall, M., McDonagh, E., Miller, R.G., Moffat, C.F., Turrell, W.R. (2018) Statement "Scotland's Marine Monitoring Actions and Their Contribution to International Efforts for a Sustained Arctic Observing System" | Arctic Observing Summit 2018 | 2018 | Policymakers | | http://www.arcticobservingsummit.org/sites/arcticobservingsummit.org/files/ID_016_2018_Berx_AOS_ShortStatement.pdf |
| Non-scientific and non-peer reviewed publications popularised publications | Raeanne Miller (SRSL), Bee Berx (MSS) and Stuart Cunningham (SAMS) have contributed to a UK and to a Scottish parliamentary consultation writing in response (as individuals). Blue-Action was highlighted in each of these responses engaging policymakers - although on a UK level | // | September 2017 | Policymakers | | https://www.gov.scot/publications/points-north-scottish-governments-nordic-baltic-policy-statement/ |

## Published peer reviewed articles

These are the articles acknowledging Blue-Action and linked to this deliverable:

| Title | Authors | Journal | DOI | Date of publication | Open Access |
|---|---|---|---|---|---|
| Atlantic water flow through the Faroese Channels | Hansen, B., Poulsen, T., Húsgarð Larsen, K. M., Hátún, H., Østerhus, S., Darelius, E., Berx, B., Quadfasel, D., and Jochumsen, K. | Ocean Science | https://doi.org/10.5194/os-13-873-2017 | 13 June 2017 | Yes |

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|---|---|---|---|---|---|
| Overflow of cold water across the Iceland–Faroe Ridge through the Western Valley | Hansen, B., Larsen, K. M. H., Olsen, S. M., Quadfasel, D., Jochumsen, K., and Østerhus, S. | Ocean Science | https://doi.org/10.5194/os-14-871-2018 | 16 Apr 2018 | Yes |
| Arctic Mediterranean exchanges: a consistent volume budget and trends in transports from two decades of observations | Østerhus, S., Woodgate, R., Valdimarsson, H., Turrell, B., de Steur, L., Quadfasel, D., Olsen, S. M., Moritz, M., Lee, C. M., Larsen, K. M. H., Jónsson, S., Johnson, C., Jochumsen, K., Hansen, B., Curry, B., Cunningham, S., and Berx, B | Ocean Science | https://doi.org/10.5194/os-15-379-2019 | 12 Apr 2019 | Yes |

**Submitted publications**

Casanova-Masjoan, M., M.D. Pérez-Hernández, R.S. Pickart, H. Valdimarsson, A. Macrander, D. Grisolía-Santos, D.J. Torres, S. Jónsson, K. Våge, and A. Hernández Guerra , Alongstream, seasonal and interannual variability of the North Icelandic Irminger Current and East Icelandic Current around Iceland, Journal of Geophysical Research: Oceans

## Uptake by the targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is the general public (PU) is and is made available to the world via CORDIS.
The recommendations presented in this document have been shared with the **scientific community** at selected scientific meetings such as those organised by the ASOF network, AGU Ocean Sciences, and at the Arctic Observing Summits in 2018 and in 2020.

In addition, the recommendations in this document have been shared with:

- **policy makers** at the AMAP meeting in 2018;
- the **UK and Scottish Parliament** by replying to consultations with the Nordic Baltic policy statement (29 Sep 2017), a statement aiming to strengthen relationships with countries in the Nordic and Baltic regions by promoting policy exchange and collaboration.
- With **policy makers at the Arctic Observing Summit 2018**, where some of the Blue-Action team members published a statement listed under *Sub-Theme 3: Leveraging Observing Systems and Networks* related to the “Scotland’s Marine Monitoring Actions and their contribution to international efforts for a sustained Arctic Observing System”.

We plan to publish these recommendations on the www.blue-action.eu website under the section Policy Feed and share them with relevant staff at EASME and DG RTD.