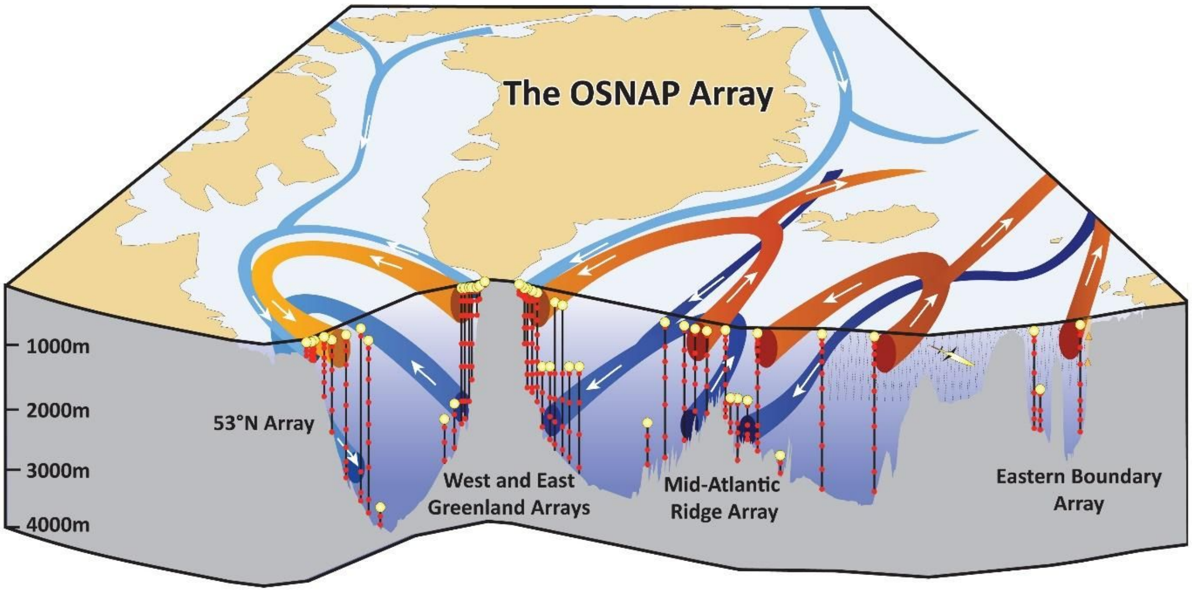
Seasonal to decadal variability of the subpolar gyre

Observed ocean processes, mechanisms of subpolar gyre circulation and propagation of heat anomalies



OSNAP array. Credits: NOC [http://www.ukosnap.org]

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Summary for publication

The aims of this Blue-Action report are to investigate the propagation of warm ocean waters from the Atlantic subpolar gyre over the Greenland-Scotland Ridge (GSR) and towards the Arctic, assess the subpolar gyre circulation in order to quantify the atmospheric and oceanic mechanisms that influence its seasonal to decadal-scale variability, and establish the link between the warm and saline eastern waters and colder and less saline western waters and the mechanisms controlling the heat and freshwater transfer from the eastern subpolar gyre to the Greenland-Scotland. The work draws primarily on data from the OSNAP (Overturning in the Subpolar North Atlantic Program) moored array and associated CTD sections, Ocean Observatories Initiative observations in the Irminger Sea, and data from Argo floats, innovative glider observations in the eastern subpolar North Atlantic, new and historical observations of flows across the Greenland-Scotland Ridge, and altimeter datasets, integrating these with model analyses.

The first 21-month record from OSNAP, coupled with Argo float data, have been described as a "sea change" in our view of overturning in the subpolar North Atlantic, with the conversion of warm, salty, shallow Atlantic waters into colder, fresher, deep waters that move southward in the Irminger and Iceland basins largely responsible for overturning and its variability in the subpolar basin. This is a departure from the prevailing view that changes in deep water formation in the Labrador Sea dominate meridional overturning circulation (MOC) variability. The observations also reveal: a highly variable MOC; the majority of the heat and freshwater transport across the OSNAP line, and its variability, is due to the variable overturning circulation rather than variations in temperature and salinity; and transports of heat northwards in the upper limb of the MOC are dominated by transports east of Reykjanes Ridge/Iceland Basin. Ongoing glider deployments from SAMS across the Rockall Trough and Hatton-Rockall plateau have made considerable progress in characterising the volume transports and seasonal variability within these North Atlantic Current branches in the Eastern Subpolar Gyre.

Further north, the structure and forcing of observed exchanges across the Greenland–Scotland Ridge have been examined. The observed variation of exchanges across the Greenland– Scotland Ridge largely reflect an overturning circulation on interannual time scales with a weaker horizontal circulation in the Nordic Seas on seasonal time scale. Considering buoyancy effects was found to be essential for the interannual time scales but not for the seasonal variability. The barotropic-like seasonal cycle of anomalous inflow and overflow following the rim of the Nordic seas can be explained by the direct influence of wind associated with changes in sea level pressure.

Volume budgets for the Arctic Mediterranean seas (AM) show overturning circulation at the Greenland-Scotland Ridge of 8.0 Sv. This compares to the mean estimate of 15.6 Sv at OSNAP$_{east}$. These suggest that over 7 Sv (> 45%) of MOC overturning measured at the OSNAP line is driven by processes occurring in the northeast section of the subpolar gyre between the OSNAP line and the GSR (Irminger Sea and Iceland Basin). To examine the processes and mechanisms involved in this region we present detailed study of spatial and temporal variability and causes of deep convection at a site in the Irminger Sea. This shows the deep convection to be a result of a complex interaction of local atmospheric processes and more remote ocean processes of inflow and eddies. Combining the observations with high resolution atmospheric reanalysis, the main source of multi-winter variability of deep convection at

this site is shown to be changes in the frequency of occurrence Greenland tip jets. These tip jets are more common in periods of positive NAO, but a positive NAO only results in strong Irminger Sea heat loss when not dominated by the East Atlantic Pattern, as the latter leads to northerly flow and tip jet suppression. Improved representation of this coupled process in ocean-atmosphere models, including its complex relationship with the two main modes of North Atlantic atmospheric variability, may prove key to obtaining reliable projections of future changes in both the overturning and climate.

The observational time-series reported here are still relatively short (just two years of OSNAP overturning and transport estimates were available for this report, though more will be available before the end of Blue-Action), but combination with modelling results allows us to examine longer-term changes.

Model analysis of the role of atmospheric forcing with respect to the oceanic conditions prevailing at the end of the 1990s on the formation of the 2000s cooling of subpolar gyre show that the changes in the heat content cannot be linked to variations of the MOC or changes in the gyre strength but are rather associated with changes in the Labrador Sea Water pathway around the gyre. In contrast, longer period climate modelling over many decades, finds anomalies in the heat content (OHC) tendency propagate around the subpolar North Atlantic on decadal time scales with a clear relationship to the phase of the AMOC. In the western subpolar North Atlantic, surface fluxes and SST appear to precede and cause AMOC changes, whereas in the east AMOC changes cause the changes in SST and surface fluxes.

Inter-annual to decadal-scale variability is also visible in biogeochemical tracers. The North Atlantic spring bloom, which is the primary food supplier to marine ecosystems in these subpolar waters, is terminated by silicate limitation every spring/summer. A new comprehensive compilation of data from the subpolar Atlantic Ocean shows clear evidence of a marked pre-bloom silicate decline of 1.5–2 µM throughout the winter mixed layer during the last 25 years. These marked fluctuations in pre-bloom silicate inventories will likely have important consequences for the spatial and temporal extent of diatom blooms, thus impacting ecosystem productivity and ocean-atmosphere climate dynamics.

Ongoing research shows that the eastern subpolar North Atlantic underwent extreme freshening during 2012 to 2016, with a magnitude never seen before in 120 years of surface measurements. The freshwater anomaly in the Iceland Basin is now propagating into the Irminger and Labrador Seas along the pathway of the subpolar circulation, and into the Nordic Seas. These changes in salinity and stratification impact the extent of deep convection and contribute to changes in the overflow waters and hence the MOC; other results and dynamical arguments suggest that MOC changes may be driven more by the interaction of these anomalies with the eastern boundary. Examination of OSNAP and GSR overflow timeseries over the coming years should help elucidate the contributions of these multi-year processes. The far-reaching impact of eastern Atlantic salinity anomalies highlights the importance of understanding, and correctly simulating, interactions between the North Atlantic Ocean dynamics and the atmosphere circulation for future climate predictions.

Work carried out

Introduction

The Atlantic Meridional Overturning Circulation (AMOC) has a distinctive role in maintaining Earth's net radiation balance. This is because it carries energy from the South Atlantic across the equator to the North Atlantic; in contrast, the Indian and Pacific Oceans and the atmosphere transfer energy away from the equator. Factors influencing this notable difference include the relative narrowness and saltiness of the Atlantic relative to the Pacific, a direct connection from the Atlantic to the Arctic Ocean, the different latitudes of Cape Agulhas and Cape Horn and the interaction with the circumpolar Southern Ocean circulation. The AMOC is responsible for 25% of the net global oceanic and atmospheric energy transport. Atlantic Ocean heat transport of around 1.3 PW is released to the atmosphere north of 26.5°N resulting in the northern hemisphere atmosphere and ocean, especially north of 60°N, being up to 2-6°C warmer than equivalent latitudes in the southern hemisphere (Buckley, M. and J. Marshall 2016) and the climate of northwestern Europe over 5º warmer in the winter than similar maritime climates in the northwestern USA (McCarthy et al., 2015).

The AMOC is characterized by warm and salty water in the upper one kilometre moving northwards throughout the Atlantic. In the subtropical North Atlantic these waters rapidly lose heat mainly through latent heat of evaporation. In the North Atlantic subpolar gyre, Nordic Sea and Arctic Ocean the upper branch of the AMOC continues to lose heat to the atmosphere but freshens due to precipitation, glacial melting, rivers and supply of low salinity water from the Pacific via the Arctic. The majority of upper waters become denser through cooling, despite the opposing tendency of freshening. These denser waters then sink, circulate and spread south through the Atlantic at depths between one and four kilometres and onward to the global ocean. The northward flowing upper branch being warmer and saltier than the returning cold, fresh branch results in a northward heat flux throughout the Atlantic and a southward freshwater flux.

There is strong observational and paleoclimate evidence that the AMOC through multidecadal variations in heat transport is linked to a multidecadal climate mode called the Atlantic Multidecadal Variability (AMV). The AMV index is associated with a dipole pattern of sea-surface temperatures. This pattern has positive North Atlantic temperatures (with stronger amplitudes in the subpolar region) and with weaker colder South Atlantic temperatures. The SST pattern is a crucial driver of climate and of enhanced decadal climate predictability. Numerous studies (e.g. see the recent review by Zhang et al. 2019) demonstrate co-variability in many societally relevant climate modes with economic and social impacts, such as ITCZ shifts, Sahel rainfall, Atlantic hurricanes, the NAO, European and North American climate, Arctic sea ice and surface air temperatures, with the AMV. There is a debate about the forcing of the 20th C AMV. Some studies (Bellomo *et al*., 2018; Bellucci *et al*., 2017; Booth *et al*., 2012; Dunstone *et al*., 2013; Murphy et al., 2017) attribute the variability to the rise and fall of aerosol forcing and its direct impact on the heating of the ocean mixed layer—arguing that internal ocean variability is less important. Other studies however emphasise that the AMV is seen to exist over many thousands of years in paleoclimate records such as ice, sediment and coral records (Gray *et al*., 2004; Mann *et al*., 2009; J. Wang *et al*., 2017).

Observational evidence supports the hypothesis that AMOC variability drives the AMV and that knowledge of the AMOC is an important source of information for enhanced decadal predictability and prediction skill for the AMV. Numerous coupled general circulation model (CGCM) experiments where AMOC anomalies are initialized in the subpolar gyre, have demonstrated greatly enhanced multidecadal predictability (e.g. Robson *et al.*, 2012; Yeager *et al*., 2012, 2018; Matei *et al.*, 2012; Yang *et al.*, 2013). The subpolar gyre seems likely to be a preferred location for the source of enhanced predictability because of the very large air-sea heat, fresh-water and momentum exchanges in this region. Very strong winter winds result in very large air-sea fluxes and deep winter mixed layers. At interannual timescales surface turbulent heat losses are associated with reduced SST (passive ocean response to atmospheric forcing). In contrast, at decadal timescales more turbulent heat flux is released during the positive (warm) AMV phase which is a negative feedback suggesting the AMOC is playing an active role at these timescales.

It is our goal to step beyond the initialization of AMOC anomalies, but also to predict those anomalies themselves. This could be possible because AMOC anomalies are a lagged response to buoyancy forcing at high latitudes connecting the AMOC upper and lower limbs. Recent observations (reported here) have produced a paradigm shift in our understanding of this connection both in the large-scale circulation and in the processes of varying modes of atmospheric circulation directly impacting subpolar gyre deep winter mixing. We here show, for the first time, that processes in the eastern subpolar gyre are of paramount importance in overturning. A very recent analysis of the adjoint ECCO model was able to reconstruct 50% of subpolar AMOC variance using the adjoint sensitivities with knowledge of sea surface temperature and salinity for the preceding two to three years (Helen Johnson, pers. comm.). Thus, we have hints that we are on the cusp of a revolution in decadal climate predictability, and this revolution will be driven by comprehensive observations of the subpolar North Atlantic.

We now link the subpolar gyre and its impact on Polar and high latitude climate. The following points have been highlighted and discussed in detail in Zhang et al. 2019.

1. The observed AMV is highly correlated with the observed multidecadal surface air temperature variations over the Arctic and the Atlantic-Arctic boundary.
2. The simulated winter Arctic sea ice decline associated with an intensified AMOC and a positive AMV phase resembles the satellite-observed winter Arctic sea ice decline pattern over the recent decades, suggesting a possible role of the AMOC and AMV in the recently observed winter Arctic sea ice decline.
3. At multidecadal timescales, the AMOC and associated Atlantic heat transport across the Arctic Circle lead the Atlantic inflow temperature in the Barents Sea, as well as the Atlantic heat transport across the Barents Sea opening by several years.
4. AMV-related stratosphere-troposphere coupling may drive changes in the polar vortex and air temperatures; specifically, the recent warm AMV phase appears to have led to weakening of the polar vortex, Arctic warming, and decreased winter sea ice extent in the Barents Sea.
5. Multidecadal AMOC variability is a significant driver for the decadal predictability of Arctic sea ice thickness in the Atlantic sector.
6. Pronounced multidecadal surface air temperature variability over the Greenland ice sheet has also been observed during the twentieth century and is significantly correlated with the observed AMV index. Many observational studies suggest that the warming of the subpolar AMV signal in the mid-1990s contributed to the rapid mass loss of the Greenland ice sheet over the recent decades.

7. The observed multidecadal variations in Arctic surface air temperature, which are highly correlated with the observed AMV index, are also anticorrelated with the observed multidecadal variations in Antarctic surface air temperature, suggesting an essential role of multidecadal AMOC variability and associated AMV in the observed bipolar seesaw over the twentieth century.

The aim of this Blue-Action deliverable is to investigate the propagation of warm ocean waters from the subpolar gyre over the GSR and towards the Arctic. We achieve this through the analysis of state-of-the-art observations of the subpolar North Atlantic conducted under the auspices of the Blue-Action Project. The report draws primarily on data from the OSNAP moored array and associated CTD sections, Ocean Observatories Initiative observations in the Irminger Sea, and data from Argo floats, innovative glider observations in the eastern subpolar North Atlantic, new and historical observations of flows across the Greenland-Scotland Ridge, and altimeter datasets.

In this section we review and synthesize results from 16 papers (13 already published), that have Blue-Action funding acknowledgements. These results are described below, ordered by published paper under the headings: Ocean processes -- description and quantification of processes such as AMOC, deep convection, currents, transports and gyre circulation, and their variability in the subpolar North Atlantic; Mechanisms of subpolar gyre circulation -- where causal links are also investigated; and Ocean heat and freshwater transports -- focussing on northward transports in the eastern subpolar North Atlantic.

Ocean processes

A sea change in our view of overturning in the subpolar North Atlantic

Lozier *et al*. 2019, *Science*. Journal Impact Factor 41.037

[SAMS, NERC, NIOZ, GEOMAR, CNRS] The first 21-month record from the Overturning in the Subpolar North Atlantic Program (OSNAP) observing system reveals a highly variable overturning circulation responsible for the majority of the heat and freshwater transport across the OSNAP line. In a departure from the prevailing view that changes in deep water formation in the Labrador Sea dominate MOC variability, these results suggest that the conversion of warm, salty, shallow Atlantic waters into colder, fresher, deep waters that move southward in the Irminger and Iceland basins is largely responsible for overturning and its variability in the subpolar basin (Figure 1).

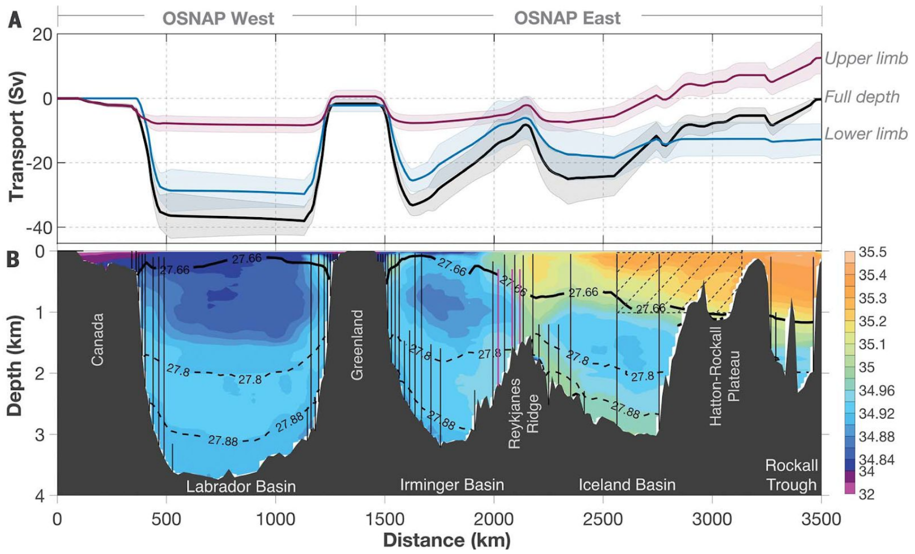

Figure 1: Transport and salinity across the OSNAP section. (A) Top-to-bottom integrated volume transport accumulated eastward starting at the western edge of the Labrador Basin (black line), with northward transport defined as positive. The upper (red line) and lower (blue line) MOC limbs are shown separately. Shading indicates one standard deviation from the 21-month mean. **(B)** The OSNAP section with moorings marked by vertical black lines. Vertical magenta lines on the western flank of the Reykjanes Ridge indicate three French moorings, which are part of the RREX program. Hatching in the eastern Iceland Basin indicates the glider survey domain. Mean salinity (coloured, with scale at the right-hand side) and potential density (contoured) are calculated from Argo and OSNAP data from August 2014 to April 2016. The thick black line denotes the potential density surface (27.66 kg m^{-3}) that separates the MOC upper and lower limbs. **Taken from Lozier et al. (2019).**

Across the Labrador Basin, the large pool of low-salinity water that reaches from the surface to ∼1500 m marks the Labrador Sea Water (LSW), the shallowest component of the MOC lower limb. The western and eastern boundary currents in the Labrador Basin have strong transports, particularly so for the lower limb where transports reach ∼30 Sv. However, the relatively small cumulative transport across the Labrador Sea in both the upper and lower limbs reveals that these opposing boundary currents are largely carrying waters of the same density, i.e., there is little density transformation or overturning across this basin during this time period.

Across OSNAP East, strong boundary currents with broader opposing flows in the basin interior are also evident in the lower limb. Here, however, there is an appreciable accumulation of southward flow (∼12 Sv). The net southward transport of the deep components of the lower limb is largely balanced by the northward-flowing North Atlantic Current, which carries warm, salty waters across the easternmost part of the OSNAP section, forming the bulk of the upper MOC limb.

These time series highlight the most notable aspect of this 21-month record, namely that the overturning circulation across OSNAP East (15.6 ± 0.8 Sv) dominates that across OSNAP West (2.1 ± 0.3 Sv), the former being ∼7 times greater than the latter. The mean MOC across the whole section is estimated as 14.9 ± 0.9 Sv. The MOC across the entire OSNAP section shows considerable temporal variability, with 30-day means from 8.1 to 24.1 Sv. OSNAP East also dominates this temporal variability. Overturning variability across this section explains 88% of the variance in the MOC across the entire section, far exceeding the contribution of OSNAP West (25%). A longer time series will aid our understanding of the relationship between these two time series.

Subpolar North Atlantic overturning and gyre-scale circulation in the summers of 2014 and 2016

Holliday *et al*. 2018. *Journal of Geophysical Research: Oceans* 123(7). Journal Impact Factor 3.235

[NERC, SAMS, GEOMAR] Two hydrographic trans-basin sections in the summers of 2014 and 2016 – along the OSNAP line marking the beginning and end of the 21 month OSNAP mooring time series reported above – provide highly spatially resolved views of the subpolar North Atlantic (SPNA) velocity and property fields on a line from Canada to Greenland to Scotland. Combining vertical geostrophic shear from the density gradient between CTD stations with observed LADCP reference velocities and Ekman velocity computed from wind stress, these observations form an independent estimate of volume, heat and freshwater transports in the summers of 2014 and 2016 which can be compared with the mooring data reported in Lozier *et al.* (2019).

The upper layer property fields changed between the two sections (Figure 2), with notably cooler and fresher conditions in Iceland Basin and Rockall Trough in OS2016. The deepest layers of the Labrador Sea and Irminger Sea exhibited cooling and freshening after deep winter convection after OS2014; interestingly, the development of a thicker layer of ventilated LSW did not result in higher export of LSW from the Labrador Sea in OS2016.

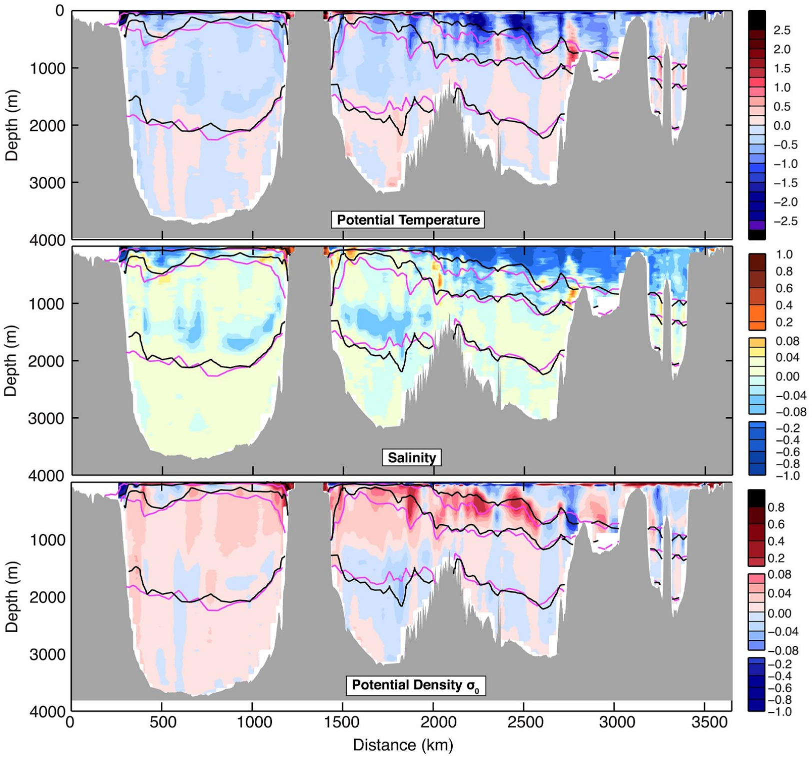

Figure 2: Property differences between the two sections (OS2016 minus OS2014). Top panel is potential temperature (°C), middle panel is salinity, and bottom panel is potential density (kg/m^3). Isopycnals 27.50, 27.70, and 27.80 kg/m^3 overlain in magenta (OS2014) and black (OS2016). **Figure taken from Holliday et al. 2018.**

Estimates of the AMOC, isopycnal (gyre-scale) transport, and heat and freshwater transport are derived from the observations. The overturning circulation, the maximum in northward transport integrated from the surface to seafloor and computed in density space, has a high range, with 20.6 ± 4.7 Sv in June–July 2014 and 10.6 ± 4.3 Sv in May–August 2016. These values are within the range of 30-day means reported from the mooring time series. Using Table 2 from Holliday *et al.* (2018) we can estimate the OSNAP West contributions to the MOC as 5.5 ± 2.1 Sv (2014) and -0.5 ± 1.3 Sv (2016). While including the uncertainty ranges these are not inconsistent with the values from the mooring array reported in Lozier *et al.* (2019), 5.5 Sv overturning in the western basin is higher than any of the 30 day means recorded in the mooring data and differences in OSNAP west overturning account for more than half the difference in estimated MOC.

The transport in the Rockall Trough has a very high range, which hints at the difficulty of measuring transport in a region of energetic mesoscale and submesoscale recirculation. Although the range of our two estimates of transport in the upper layer is high (<27.50 kg m3, 0.7 ± 0.9 Sv, and 7.6 ± 1.0 Sv; Table 2), they lie within the range estimated from four decades of historical temperature and salinity data in the same location (Holliday *et al.,* 2015, 2000). This large range of transports in the eastern basin, supports the findings from the continuous records from the OSNAP moorings that the eastern basin dominates the temporal variability.

Structure and transport of the North Atlantic Current in the eastern Subpolar Gyre from sustained glider observations

Houpert *et al*. 2018. *Journal of Geophysical Research: Oceans* 123 (8). Journal Impact Factor 3.235

[SAMS] The Rockall Plateau (RP), also known as Rockall-Hatton Plateau, is characterized by a shallow topography and is formed by the Hatton Bank (HB), the Hatton Rockall Basin (HRB), and the Rockall Bank (RB. Weak stratification leads to a small radius of deformation (<10 km; Chelton et al., 1998), this radius of deformation, a characteristic scale of the mesoscale eddy field, requires an appropriate sampling strategy to resolve and adequately characterize the flow. All previous observations from research vessels in this region have a nominal station spacing too large (about 30–50 km; Bacon, 1997; Holliday *et al.*, 2015; Sarafanov *et al.,* 2012) to correctly resolve the mesoscale field over the RP.

Repeat glider sections obtained during 2014–2016, as part of the Overturning in the Subpolar North Atlantic Program, are used to quantify the circulation and transport of North Atlantic Current (NAC) branches over the Rockall Plateau. Using 16 glider sections collected along 58◦N and between 21◦W and 15◦W, absolute geostrophic velocities are calculated, and subsequently the horizontal and vertical structure of the transport is characterized (Figure 3). The annual mean northward transport (± standard deviation) is 5.1 ± 3.2 Sv over the Rockall Plateau. In summer (May to October), the mean absolute geostrophic transport referenced to glider DAC is 6.7 ± 2.6 Sv in summer, with three main branches: (i) the Hatton Bank Jet, a northward flow of 6.3 ± 2.1 Sv along the western flank of the Hatton Bank (20.5°W to 18.5°W); (ii) a southward flow of 1.1 ± 1.4 Sv along the western flank of the Hatton-Rockall Basin (18.5°W to 16.0°W); and (iii) the Rockall Bank Jet, a northward flow of 1.5 ± 0.7 Sv along the eastern flank of the Hatton-Rockall Basin (16°Wto 15°W). On average, these three branches are bathymetrically steered, particularly on the steep slopes of the Hatton and Rockall Banks. The net meridional transport in summer accounts for 43% of the total NAC transport of upper-ocean waters (σ_0 < 27.55) estimated by Sarafanov *et al.* (2012) and Rossby *et al.* (2017) along 59.5°N, between the

Reykjanes Ridge and Scotland. These transports are consistent with those of Lozier *et al.* (2019) and Holliday *et al.* (2018), above.

With the NAC branches in the Central Iceland Basin and in the Rockall Trough, the Hatton Bank Jet is one of the main NAC pathways in the Eastern Subpolar Gyre. The Hatton Bank Jet appears to be quasi-permanent as it can be seen on both mean absolute surface geostrophic currents from altimetry data and on mean absolute geostrophic sections from repeated glider observations along 58°N. However, it can be occasionally deflected toward the Iceland Basin due to strong mesoscale eddy activity west of the Hatton Bank.

The transport on the western and eastern parts of the Hatton-Rockall Basin is mostly independent of depth during summer, while 30% of the Hatton Bank Jet transport is baroclinic. During winter, transports have a higher variability and geostrophic currents are more baroclinic. The winter intensification of surface buoyancy forcing could be the reason for an enhanced baroclinic shear and winter subpolar mode formation, which may lead to an increase of current variability in the subpolar gyre. More glider sections in winter are needed if one wants to fully characterize and quantify the excitation of wintertime currents by surface buoyancy forcing. Fewer winter observations are available due to logistical difficulties and poor weather conditions, leading to a higher uncertainty on the mean winter meridional transport. However, additional observing efforts are being made to ensure a permanent monitoring of the Hatton Bank Jet in winter.

Comparisons with altimetry-based estimates indicate similar large-scale circulation patterns; however, altimetry data are unable to resolve the small mesoscale current bands in the Hatton-Rockall Basin, which appear to be due to the mapping methodology combined with altimeter constellation sampling capability.

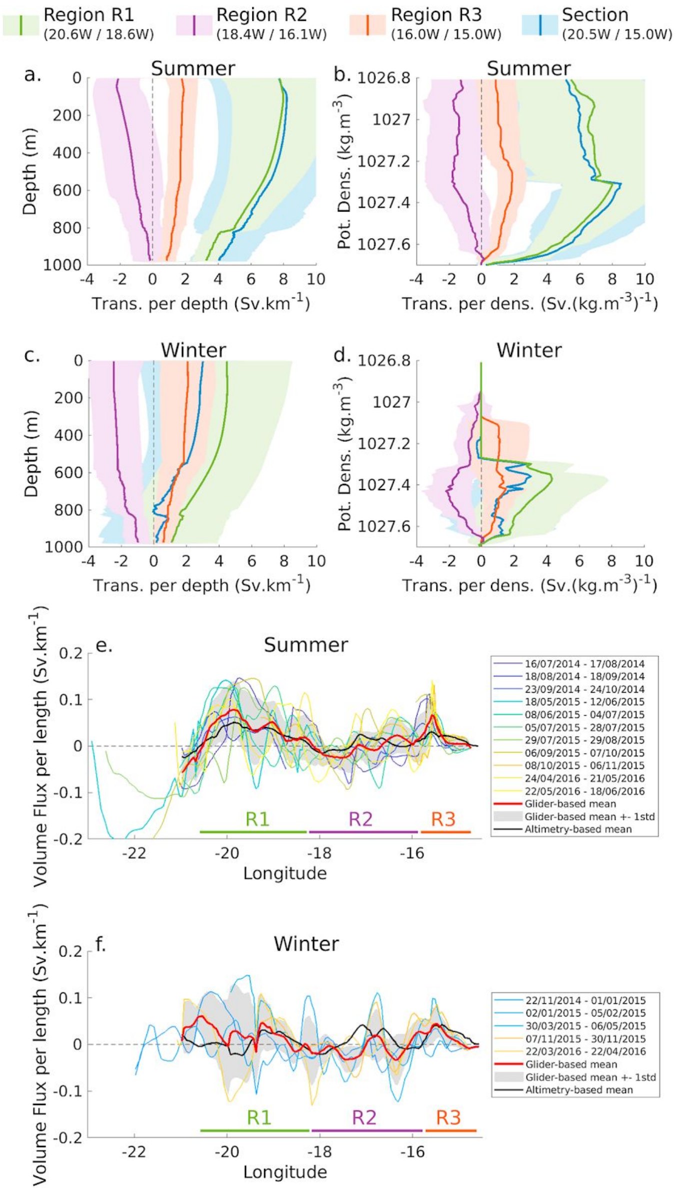

Figure 3: Mean summer (a, b, e) and winter (c, d, f) absolute meridional geostrophic velocity transport by longitude as a function of depth (a, c), density (b, d), and integrated by depth as a function of longitude (e, f). Shaded areas (in panels a–d) correspond to the mean transport ±1 standard deviation for Region R1 -- Hatton Bank Jet (green), Region R2 -- Hatton-Rockall Basin (purple), Region R3 -- Rockall Bank Jet (orange), and the total section (blue). **Taken from Houpert et al. 2018.**

Seasonal cycles of oceanic transports in the eastern Subpolar North Atlantic

Gary *et al*. 2018. *Journal of Geophysical Research: Oceans* 123 (2). Journal Impact Factor 3.235

[SAMS] The variability of the Atlantic Meridional Overturning Circulation (AMOC) may play a role in sea surface temperature predictions on seasonal to decadal time scales. Therefore, AMOC seasonal cycles are a potential baseline for interpreting predictions. This study presents estimates for the seasonal cycle of transports of volume, temperature, and freshwater associated with the upper limb of the AMOC in the eastern subpolar North Atlantic on the Extended Ellett Line hydrographic section between Scotland and Iceland. Due to weather, ship-based observations are primarily in summer. Recent glider observations during other seasons present an opportunity to investigate the seasonal variability in the upper layer of the AMOC. First, a new method to quality control and merge ship, float, and glider hydrographic observations is documented. This method accounts for the different spatial sampling rates of the three platforms. The merged observations are used to compute seasonal cycles of volume, temperature, and freshwater transports in the Rockall Trough. These estimates are similar to the seasonal cycles in two eddy-resolving ocean models. Volume transport appears to be the primary factor modulating other Rockall Trough transports. Finally, it is shown that the weakest transports occur in summer, consistent with seasonal changes in the regional-scale wind stress curl. Although the seasonal cycle is weak compared to other variability in this region, the amplitude of the seasonal cycle in the Rockall Trough, roughly 0.5–1 Sv about a mean of 3.4 Sv, may account for up to 7–14% of the heat flux between Scotland and Greenland.

Transport and variability of the Irminger Current: 2014-2016

de Jong *et al*., in prep

[NIOZ] The northeastward flow of warm, salinity Subpolar Mode Water and dense North East Atlantic Deep Water along the western flank of the Reykjanes Ridge is an important component in the overturning of the North Atlantic subpolar gyre. Part of the Irminger Current continues north through Denmark Strait and into the Iceland Sea in the Icelandic Irminger Current, the rest flows cyclonically around the basin and southward along the East Greenland shelf where these relatively warm waters impact marine terminating glaciers.

The Irminger Current array observed the full-depth volume transport, temperature and salinity from July 2014 to July 2016 as part of OSNAP (Figure 4). While in the mean field the Irminger Current is composed of two current cores separated by southward flow, this setup is highly variable on shorter time scales. At times all moorings measure northward transport, while at other times the southward flow is strengthened.

Overall, both current cores contribute equally to the volume transport, which was found to be 10.6 Sv with a standard deviation of 9.3 Sv and a standard error of 1.6 Sv. Mean heat and freshwater transport were 0.21 PW and -22 mSv respectively. The mean volume transport was lower (8.4 Sv) during the first deployment than during the second (12.3 Sv). In the second deployment, both current cores appear to be stronger and fewer current reversals are seen in the total volume transport. Possible this change over the winter of 2014-2015 is related to the return of deep convection in the centre of the basin.
The westernmost extent of the western Irminger Current core occasionally moves out of reach of the mooring array, making it hard to estimate its full transport. On time scales of three months and longer the surface velocities from altimetry across the array agree with the current structure seen in the mooring data. This opens up the opportunity to use altimetry data to define the westernmost boundary of the core. However, the high variability on shorter time scales is not adequately captured by altimetry.

Preliminary results have been presented at the Irminger Sea workshop (https://doi.org/10.5281/zenodo.1283847) and the Ocean Sciences Meeting in 2018. A manuscript is currently in preparation (de Jong et al. to be submitted to JGR Oceans).

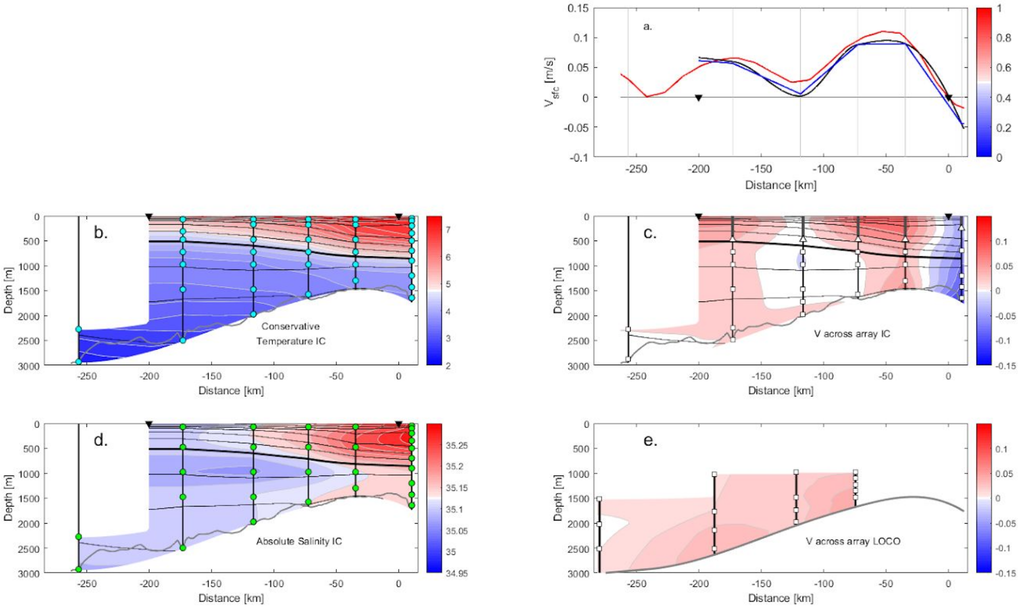

Figure 4: Results from the Irminger Current array from July 2014 to July 2016. A) Mean surface velocities at the moorings in blue (linear interpolation) and black (spline interpolation) and mean surface velocity from altimetry (red) over the same period. Mean fields of conservative temperature (B), velocity across the array (C), absolute salinity (D). Isopycnals are drawn in black, the 27.7 kg m^{-3} is indicated with a thick black line. E) mean across velocity field from the LOCO array deployed at the same location from August 2003 to October 2004. Mooring and instrument positions for each of the variables are shown in the plots with vertical black lines and markers. Black triangles at the top indicate the area over which the total transport is calculated.

Arctic Mediterranean exchanges: a consistent volume budget and trends in transports from two decades of observations

Østerhus *et al.*, 2019. *Ocean Science* 15 (2). Journal Impact Factor 2.539

[MRI, (MSS), HAV, NIOZ] The Arctic Mediterranean (AM) is the collective name for the Arctic Ocean, the Nordic Seas, and their adjacent shelf seas. Water enters into this region through the Bering Strait (Pacific inflow) and through the passages across the Greenland–Scotland Ridge (Atlantic inflow) and is modified within the AM. The modified waters leave the AM in several flow branches which are grouped into two different categories: (1) overflow of dense water through the deep passages across the Greenland–Scotland Ridge, and (2) outflow of light water – here termed surface outflow – on both sides of Greenland. These exchanges transport heat and salt into and out of the AM and are important for conditions in the AM. They are also part of the global ocean circulation and climate system. Attempts to quantify the transports by various methods have been made for many years, but only recently the observational coverage has become sufficiently complete to allow an integrated assessment of the AM exchanges based solely on observations.

This study focuses on the transport of water, data are collected on volume transport for as many AM-exchange branches as possible between 1993 and 2015 (Figure 5). The total AM import (oceanic inflows plus freshwater) is found to be 9.1 Sv (sverdrup, 1 Sv = 10^6 m^3 s^{-1}) with an estimated uncertainty of 0.7 Sv and has the amplitude of the seasonal variation close to 1 Sv and maximum import in October. Roughly one-third of the imported water leaves the AM as surface outflow with the remaining two-thirds leaving as overflow. The overflow water is mainly produced from modified Atlantic inflow and around 70% of the total Atlantic inflow is converted into overflow, indicating a strong coupling between these two exchanges. The surface outflow is fed from the Pacific inflow and freshwater (runoff and precipitation) but is still approximately two thirds of modified Atlantic water.

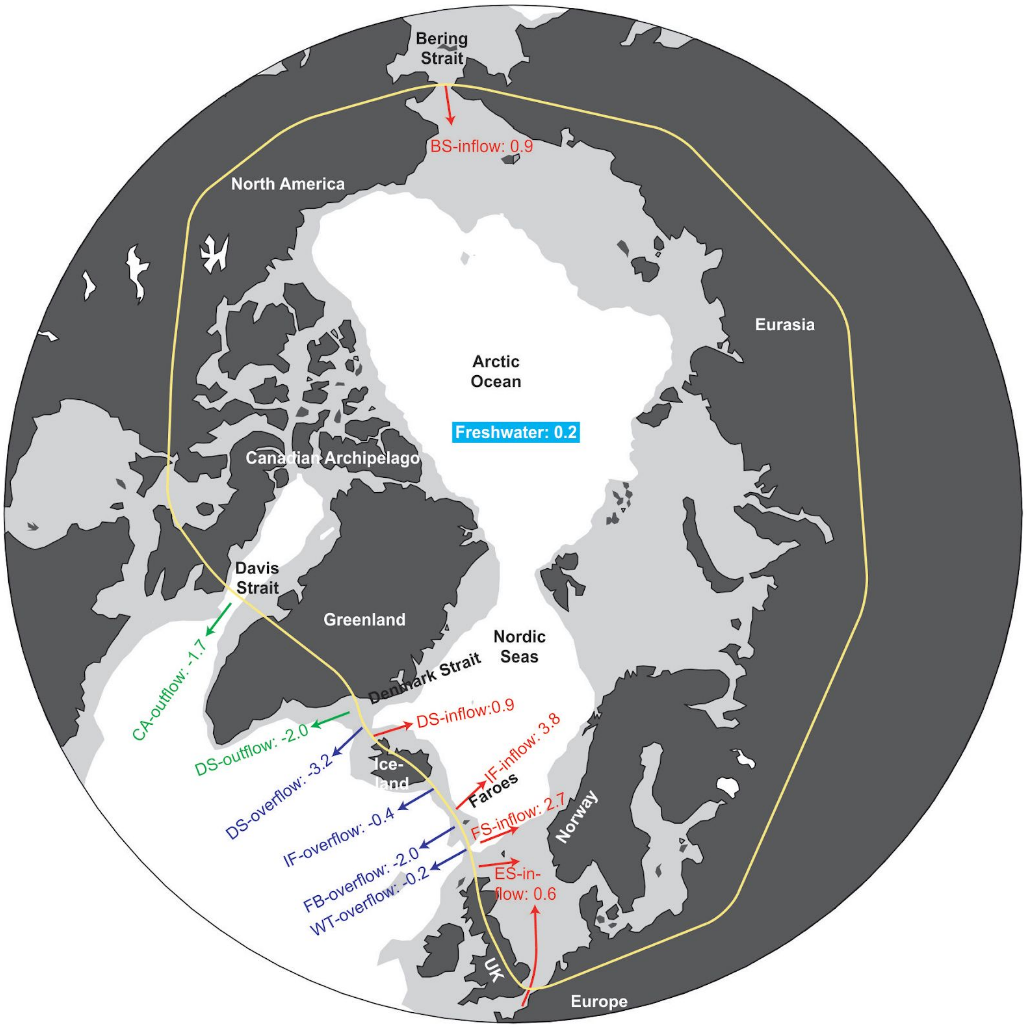

Figure 5: The Arctic Mediterranean (roughly represented by the oceanic areas within the yellow curve) and its exchanges with the rest of the World Ocean. Land areas are black. Ocean areas shallower than 1000m are light

grey. Red arrows indicate inflow branches. Dark blue arrows indicate overflow branches. Green arrows indicate surface outflow branches. **Taken from Østerhus et al., 2019.**

For the inflow branches and the two main overflow branches (Denmark Strait and Faroe Bank Channel), systematic monitoring of volume transport has been established since the mid-1990s, and this enables us to estimate trends for the AM exchanges as a whole. At the 95% confidence level, only the inflow of Pacific water through the Bering Strait showed a statistically significant trend, which was positive. Both the total AM inflow and the combined transport of the two main overflow branches also showed trends consistent with strengthening, but they were not statistically significant. They do suggest, however, that any significant weakening of these flows during the last two decades is unlikely and the overall message is that the AM exchanges remained remarkably stable in the period from the mid-1990s to the mid-2010s. The overflows are the densest source water for the deep limb of the North Atlantic part of the meridional overturning circulation (AMOC), and this conclusion argues that the reported weakening of the AMOC was not due to overflow weakening or reduced overturning in the AM. Although the combined data set has made it possible to establish a consistent budget for the AM exchanges, the observational coverage for some of the branches is limited, which introduces considerable uncertainty. This lack of coverage is especially extreme for the surface outflow through the Denmark Strait, the overflow across the Iceland–Faroe Ridge, and the inflow over the Scottish shelf. We recommend that more effort is put into observing these flows as well as maintaining the monitoring systems established for the other exchange branches.

Atlantic water flow through the Faroese Channels

Hansen *et al*., 2017. *Ocean Science* 13 (6). Journal Impact Factor 2.539

[HAV, NORCE, MSS, UHAM] By far most of the warm Atlantic water flow towards the Arctic passes between Iceland and Scotland (Østerhus *et al*., 2019) in two current branches. The northernmost of these, the "IF-inflow", flows between Iceland and the Faroes and is focused into the Faroe Current. The other branch, the "FS-inflow" flows through the Faroe-Shetland Channel and over the Scottish shelf. A part of the Faroe Current does, however, bifurcate into the Faroe-Shetland Channel and flows southwestwards over the Faroe slope as the "Southern Faroe Current" (SFC in Figure 6), but the further fate of it has been debated.

Traditionally, the IF-inflow and the FS-inflow have been monitored separately and for the mass and heat budget it, therefore, has to be clarified whether the Southern Faroe Current recirculates within the Faroe-Shetland Channel and contributes to the FS-inflow, or circulates the Faroe Plateau. In an attempt to settle this debate, the available observational material was analysed within Blue-Action (Hansen *et al.*, 2017) and the result is summarized in Figure 6.

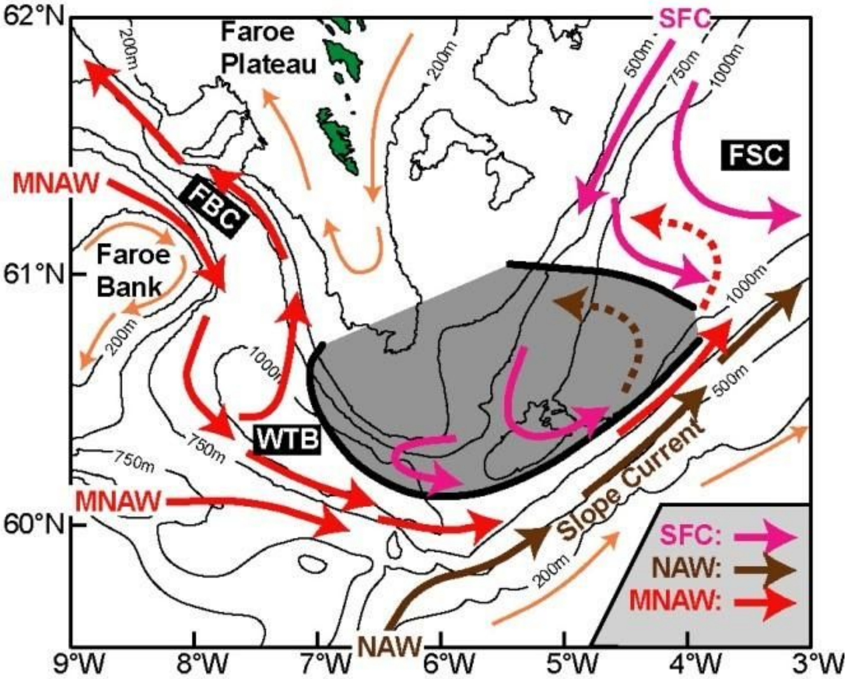

Figure 6:. The flow of Atlantic water between the Faroes and Scotland. Traditionally, the Atlantic waters coming from the west have been split into two different water masses: the "North Atlantic Water" (NAW, brown arrows) that largely follow the continental slope and Modified North Atlantic Water" (MNAW, red arrows) with a more oceanic origin. The "Southern Faroe Current" (SFC, purple arrows) carries MNAW that has been cooled and freshened north of the Faroes. According to Hansen et al. (2017), the SFC recirculates within the Faroe-Shetland Channel (FSC) or the eastern parts of the Wyville Thomson Basin (WTB) but does not continue into the Faroe Bank Channel (FBC). The frontal region between the MNAW from the west and the SFC varies within the shaded region. Orange arrows indicate shelf circulation. **Taken from Hansen *et al.* 2017.**

Atlantic Meridional Overturning Circulation: Observed transport and variability

Frajka-Williams et al., 2019 *Frontiers in Marine Science* 6 (June). Journal Impact Factor 3.086

[NERC, SAMS, CNRS, GEOMAR, NCAR] This paper summarizes observational efforts in the Atlantic to measure the continuously varying strength of the AMOC. From first trans-basin measurements retrieved at 26◦N by the RAPID array, a number of startling results have emerged (summarized in Srokosz and Bryden, 2015): that the AMOC ranged from 4 to 35 Sv over a single year, had a seasonal cycle with amplitude over 5 Sv, and that the dip in 2009/10 of 30% exceeded the range of interannual variability found in climate models. The international efforts to measure the AMOC in the Atlantic at a range of latitudes have delivered new understanding of AMOC variability, its structure and meridional coherence. In situ mooring arrays form the primary measurements of the large-scale meridional circulation, though the methodology used varies between latitudes and while some velocities and water mass properties are measured directly, there are also indirect inclusions of Ekman transport at the surface from reanalysis winds. These observations have informed and continue to inform numerical modelling efforts, which show striking differences between the AMOC mean state and variability amongst models (Danabasoglu *et al.*, 2014, 2016). Due to the differences between simulations of the AMOC, and the importance of the AMOC in the climate system, sustained observations are needed to further advance mechanistic understanding of this large-scale circulation and improve numerical models and climate simulations.

While the in-situ arrays have demonstrated the value of high time resolution near boundary observations, the cost of these arrays is significant and still leaves gaps in AMOC observing. A range of observational techniques have been used to estimate the AMOC strength and variability both directly (from satellite and hydrographic data) and indirectly (through budgetary approaches or inverse methods). However, sparse sampling, particularly by the Argo float array, combined with the importance of boundary measurements to resolving trans-basin transports, may mean that the uncertainties associated with these methods limit their utility in answering outstanding questions about AMOC mechanisms and impacts. In the future, while it is likely that a small number of observing arrays are necessary to maintain high quality, full time resolution estimates of the AMOC strength, significant gains can be made through monitoring efforts using distributed observations (satellite/Argo) or reduced costs of moored instrumentation with bottom pressure approaches. These approaches can reduce the costs of the AMOC-specific observations, while broadening the geographic coverage beyond individual latitudes. However, transitioning to new methods of sustained observing must be done with care to maintain the continuity of observations and data quality (Karl *et al.,* 1996; National Research Council, 1999; World Meteorological Organization, 2008; Weatherhead *et al.,* 2017). In particular, two recommendations made by Karl *et al.* (1996) and repeated many times subsequently are that

- Prior to implementing changes to existing systems or introducing new observing systems an assessment of the effects on long-term climate monitoring should be standard practice, and
- Overlapping measurements of both the old and new observing systems for in-situ and satellite data must become standard practice for critical climate variables.

These principles have been adopted in the development of the Global Tropical Moored Buoy Array (Freitag *et al.,* 2018) and they apply equally well to observing systems for the AMOC. The problem with overlapping new and old measurement systems or instruments is that in the short-term there is an increased cost through operating both, though in the longer-term there may be significant savings. This approach, also known as parallel testing, should be the preferred approach (National Research Council, 1999; World Meteorological Organization, 2008).

While the observational records of the AMOC transport variability are relatively short, we have learned a great deal about the structure and variability of the AMOC volume, heat and freshwater transports, its response to wind forcing, and its meridional coherence (or lack thereof) between latitudes. As the records outside of the subtropical North Atlantic increase in length, inter-comparisons between latitudes will permit understanding of the AMOC as a circulation system spanning gyres and hemispheres. New developments for observing carbon transports will illuminate the role of the AMOC in carbon storage in the deep ocean. As tools for comparing transports between observations and models are developed, we anticipate further gains in understanding of the AMOC mechanisms, drivers and impacts, and interactions between the ocean circulation and the atmosphere or cryosphere. These observing systems add considerable new knowledge to large-scale ocean circulation dynamics.

Mechanisms

Structure and forcing of observed exchanges across the Greenland–Scotland Ridge

Bringedal *et al*., 2018. *Journal of Climate* 31 (24). Journal Impact Factor 4.805

This study describes the observed volume transport variability of four volume transports crossing the Greenland–Scotland Ridge: the inflow of warm Atlantic water through the Faroe–Shetland Channel and Denmark Strait and the overflow of cold water through the Faroe Bank Channel and Denmark Strait (Figure 7). By comparing these transport time series with re-analysed sea level pressure, wind, and sea surface height, common forcing mechanisms on seasonal and interannual time scales can be deduced. The Atlantic water measured north of the Faroe Islands in the Faroe Current was not considered regarding common forcing mechanisms as the statistical analysis revealed it being unrelated to the other transports on these time scales.

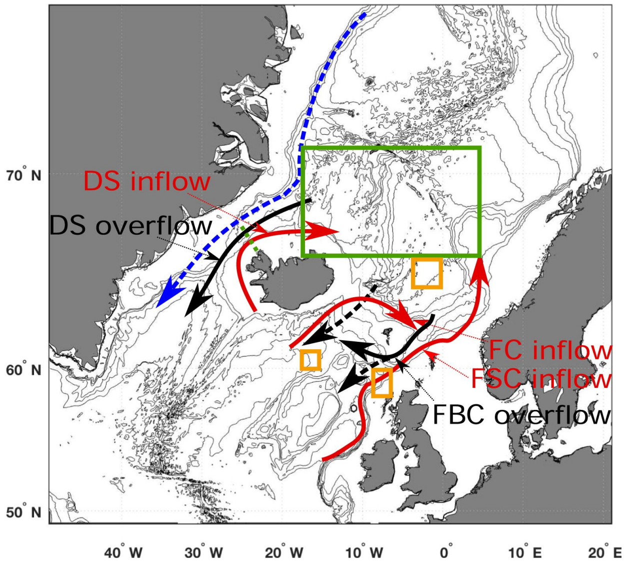

Figure 7: The exchanges across the Greenland–Scotland Ridge. Red arrows indicate AW inflow, and black indicate OW; solid lines are the observed flows considered in this study. **Taken from Bringedal *et al.* 2018.**

Concerning the seasonal cycle, the four transports can be interpreted as being part of a cyclonic circulation encompassing the Nordic seas driven by the wind stress or wind stress curl near the Greenland–Scotland Ridge. Supported by a simple two-layer model based on Straneo (2006), the wind stress curl through a topographic Sverdrup relation and the wind stress through an Ekman relation can both account for the observed seasonal variability of the four transports following the rim of the Nordic seas, with respect to both seasonal phase and amplitude. Baroclinic processes through atmospheric heat loss play a minor role for the seasonal variability.

Moving into longer time scales, the Greenland–Scotland Ridge exchanges can to some extent still be interpreted as part of a barotropic, cyclonic circulation, but baroclinic mechanisms gain importance. The Faroe Bank Channel overflow and Faroe–Shetland Channel inflow relate to a barotropic and total pressure difference across the ridge, but the connection between the Faroe Bank Channel overflow and the barotropic pressure difference is less pronounced after 2004. The interannual variabilities of the Faroe Bank Channel and Denmark Strait overflows shift from being anti-phased to in phase during the observation period, which is linked to a shift from dominant barotropic to common baroclinic forcing mechanisms. The Faroe Bank Channel overflow is influenced by wind induced barotropic forcing on both seasonal and longer time scales, and we find that this connection was particularly strong before 2005.

Estimating the Nordic seas overturning and horizontal circulations through these four volume transports provides insight to the extent of horizontal transport and overturning transformation occurring within the Nordic seas, as well as their possible relations to forcing mechanisms. In the mean, the Greenland–Scotland Ridge exchanges reflect an overturning transformation. The seasonal variability is mainly a horizontal, cyclonic circulation associated with wind stress or wind stress curl (Figure 8), while the interannual variability is dominated by overturning that can be linked to winds from the south and increased SSH within the Nordic seas (Figure 9).

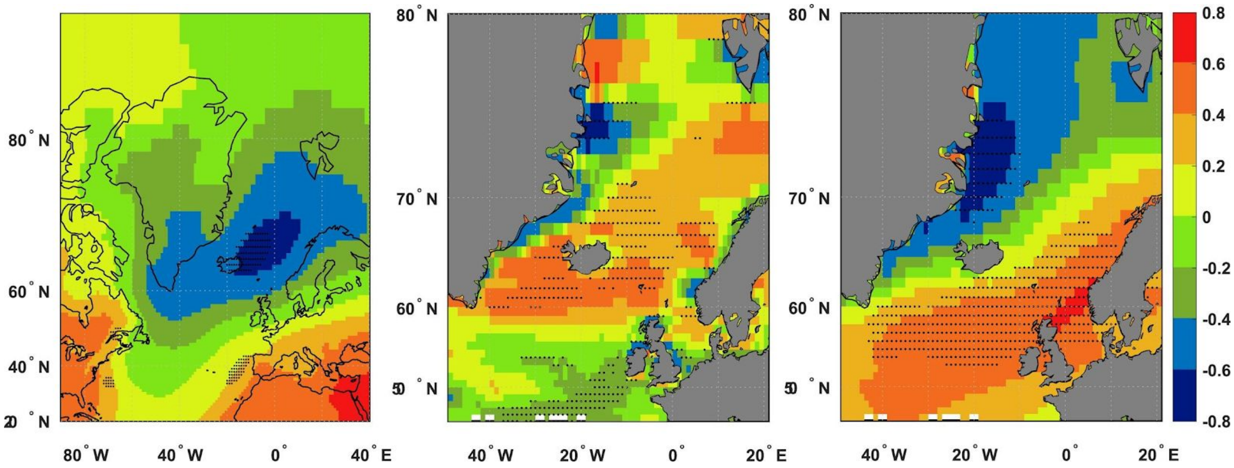

Figure 8:Atmospheric forcing of the seasonal horizontal circulation. Correlation maps between the monthly horizontal circulation (PC1) and (left) gridded SLP, (centre) wind stress curl, and (right) southwesterly wind stress. Dots indicate significant correlations. **Taken from Bringedal et al. 2018.**

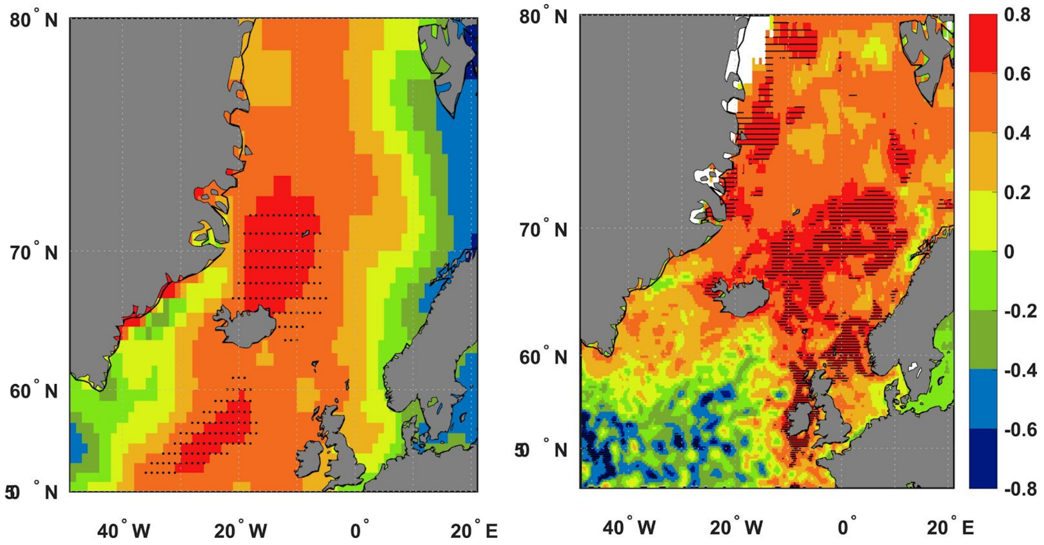

Figure 9: Atmospheric forcing of the annual overturning circulation. Correlation maps between the annual overturning circulation (PC1) and (left) gridded southern winds and (right) SSH. Dots indicate significant correlations. **Taken from Bringedal et al. 2018.**

In summary:

- The observed variable exchanges across the Greenland– Scotland Ridge reflect a horizontal circulation in the Nordic seas on seasonal time scales and to a larger extent an overturning circulation on interannual time scales.
- The barotropic-like seasonal cycle of anomalous inflow and overflow following the rim of the Nordic seas can be explained by the direct influence of wind associated with changes in sea level pressure.
- Buoyancy effects are not essential for the seasonal variability but must be accounted for when considering interannual time scales.

Deep convection in the Irminger Sea observed with a dense mooring array. Oceanography

de Jong *et al.*, 2018. *Oceanography* 31 (1, SI). Journal Impact Factor 3.913

[NIOZ, GEOMAR] Deep convection, or the transformation of surface waters to deeper waters through strong atmospheric cooling, occurs both in the Labrador Sea and in the Irminger Sea. In the Irminger Sea it has been studied with the Long-term Ocean Circulation Observations (LOCO, NIOZ) and Central Irminger Sea (CIS, GEOMAR) moorings since 2003. The addition of the Ocean Observatories Initiative (OOI, NSF) moorings in 2014 made this area one of the densest observed convection sites. A detailed inter-comparison of the onset and evolution of deep convection between these three different ocean observing platforms within a radius of 50 km in the Irminger Sea (Figure 10) led to interesting new insights: even though the onset and evolution is significantly different, the final maximum mixed layer depths reached during the strong winter of 2014-15 were nearly identical at the different sites. Despite the fact that the northernmost site was subject to strongest atmospheric cooling, the southernmost site undergoes convection earlier due to preconditioning and cold inflow from the south. There are more intermittent warm events (eddies) disrupting the formation of mixed layer depths in the north due to the proximity of the warm Irminger Current. Results were presented at the Irminger Sea workshop, the Blue-Action GA, and have been published in the Oceanography magazine (de Jong et al., 2018; https://doi.org/10.5281/zenodo.1283847, http://doi.org/10.5281/zenodo.1283909 , https://zenodo.org/record/1284029).

The LOCO and CIS moorings were recovered in the summer of 2018 and will not be redeployed. This comparison study with the OOI moorings, facilitates the merging of these overlapping time series into one record of deep convection in the Irminger Sea.

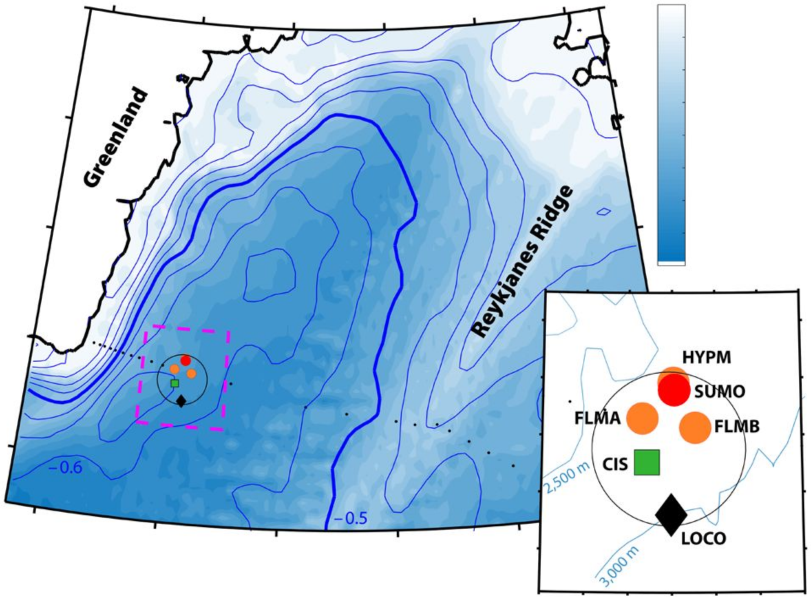

Figure 10 Locations of Irminger Sea moorings. Blue lines show mean sea surface height from altimetry. **Taken from de Jong et al., (2018).**

Extreme variability in Irminger Sea winter heat loss revealed by Ocean Observatories Initiative mooring and the ERA5 reanalysis

Josey *et al*., 2019. *Geophysical Research Letters* 46 (1). Journal Impact Factor 4.578

[NERC, NIOZ, GEOMAR] The high-latitude North Atlantic is one of two main dense water formation sites in the global ocean, the other being the Antarctic coastal seas of the Southern Ocean. In the North Atlantic, formation of dense water has long been known to take place in the Labrador and Nordic Seas and was also suggested to occur in the Irminger Sea. This remained under debate (de Jong *et al.,* 2012; Pickart *et al.,* 2008) until recently. However, mooring and Argo profiling float observations now provide unequivocal evidence for Irminger Sea deep convection (de Jong & de Steur, 2016; de Jong *et al.,* 2018; Fröb *et al.,* 2016) and highlight the need for better understanding of ocean-atmosphere interaction in this basin.

Ground-breaking measurements from the ocean observatories initiative Irminger Sea surface mooring (60°N, 39°300W) are presented that provide the first in situ characterization of multi-winter surface heat exchange at a high latitude North Atlantic site. They reveal strong variability (December 2014 net heat loss nearly 50% greater than December 2015) due primarily to variations in frequency of intense short timescale (1–3 days) forcing. Combining the observations with the new high resolution European Centre for Medium Range Weather Forecasts (ECMWF) Reanalysis 5 (ERA5) atmospheric reanalysis, the main source of multi-winter variability is shown to be changes in the frequency of Greenland tip jets (present on 15 days in December 2014 and 3 days in December 2015) that can result in hourly mean heat loss exceeding 800 W m^{-2}. Furthermore, in contrast to the prevailing view that positive NAO (North Atlantic Oscillation) conditions favour tip jet formation, and thus Irminger Sea deep convection, we have developed an alternative picture that recognizes the importance of the East Atlantic Pattern (EAP). Specifically, a positive NAO only results in strong Irminger Sea heat loss when not dominated by the EAP, as the latter leads to northerly flow and tip jet suppression (Figure 11).

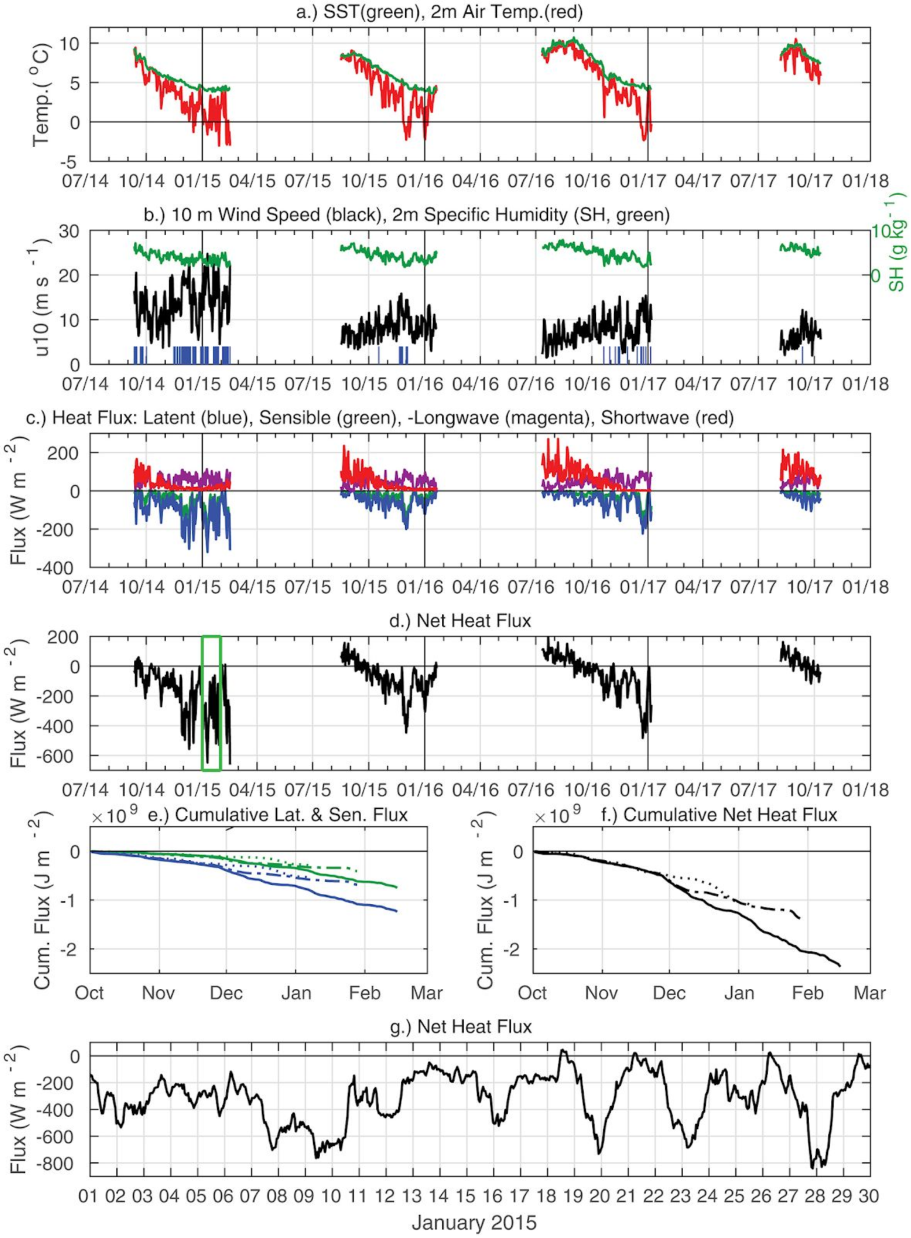

Figure 11: SUMO daily mean time series of (a) SST and 2-m air temperature; (b) 2-m specific humidity and 10-m wind speed, short blue vertical lines show tip jet days; (c) latent, sensible heat, net longwave (scaled by −1 for clarity) and net shortwave flux; and (d) net heat flux. (e, f) Cumulative daily mean time series beginning 1 October for 2014–2015 (solid line), 2015–2016 (dash-dotted line), and 2016–2017 (dotted line) are also shown for (e) latent and sensible heat flux and (f) net heat flux. (g) OOI hourly time series of net air-sea heat flux for January 2015. The green box in panel (d) indicates the time period shown in panel (g). SUMO = surface flux mooring; SST = sea surface temperature; OOI = ocean observatories initiative. **Taken from Josey *et al*. 2019.**

The analysis focuses on the novel OOI SUMO observations. The OOI Irminger Sea array contains a further three moorings making subsurface measurements (de Jong et al., 2018). Future work using all four moorings will enable the response of the subsurface ocean to tip jets and the potential dependence on NAO/EAP state to be explored in detail. This will benefit from the fifth SUMO deployment that has the potential to provide data through winter 2018–2019. Additionally, we plan to use the full multidecadal period covered by ERA5 to investigate the relationship between tip jet frequency and atmospheric mode state across a wider range of mode conditions. This has the potential to shed light on the direct relationship between Irminger Sea heat loss and consequent deep convection and the indirect influence on convection of variations in the relative states of the NAO and EAP over the past 60 years. A further question that should be addressed as a direction for subsequent research is whether projected changes in the NAO (e.g., Gillett & Fyfe, 2013) and EAP in response to climate forcing are likely to influence the frequency and strength of future Irminger Sea heat loss/deep convection.

To conclude, we note that despite receiving relatively little attention compared to the Labrador and Nordic Seas in the past, the Irminger Sea is increasingly recognized as an important component of the high-latitude North Atlantic climate system. The novel observations reported here of strong multi-winter variability in Irminger Sea heat loss have implications for dense water formation at the headwaters of the Atlantic overturning circulation.

On the Recent Ambiguity of the North Atlantic Subpolar Gyre Index

Hátún and Chafik, 2018. *Journal of Geophysical Research: Oceans* 123 (8). Journal Impact Factor 3.235

[HAV] Hátún and Chafik (2018) assess the atmospheric and oceanic mechanisms, which drive the decadal-scale variability in the North Atlantic subpolar gyre circulation. The so-called gyre index appears to be related to core aspects of the subpolar gyre, meridional overturning circulation, hydrographic properties in the Atlantic inflows towards the Arctic and in marine ecosystems in the northeast Atlantic Ocean. Recent publications (Foukal and Lozier, 2017), however, present a more linear version of this index with less of the key interannual-to-decadal variability. This has introduced uncertainty about the meaning and usefulness of the gyre index. It is claimed that these concerns are primarily caused by the fact that the recently produced ‘gyre index’ is not the same as the original gyre index and discuss possible reasons. The new publications (Berx & Payne, 2017; Foukal & Lozier, 2017; Hátún, *et al*., 2017) rigidly treated the first principal component obtained from an Empirical Orthogonal Function (EOF) analysis of the sea surface height (SSH) as the gyre index. This was an error, since most of the characteristic variability in the gyre index, which explains several climatic as well as ecological aspects of the subpolar North Atlantic, now appear in the second principal component (Figure 12). This commentary does not provide an in-depth analysis of the updated altimetry dataset, and the search for a suitable direct metric for the subpolar gyre shape/dynamics, based on more in-depth analysis, therefore remains warranted.

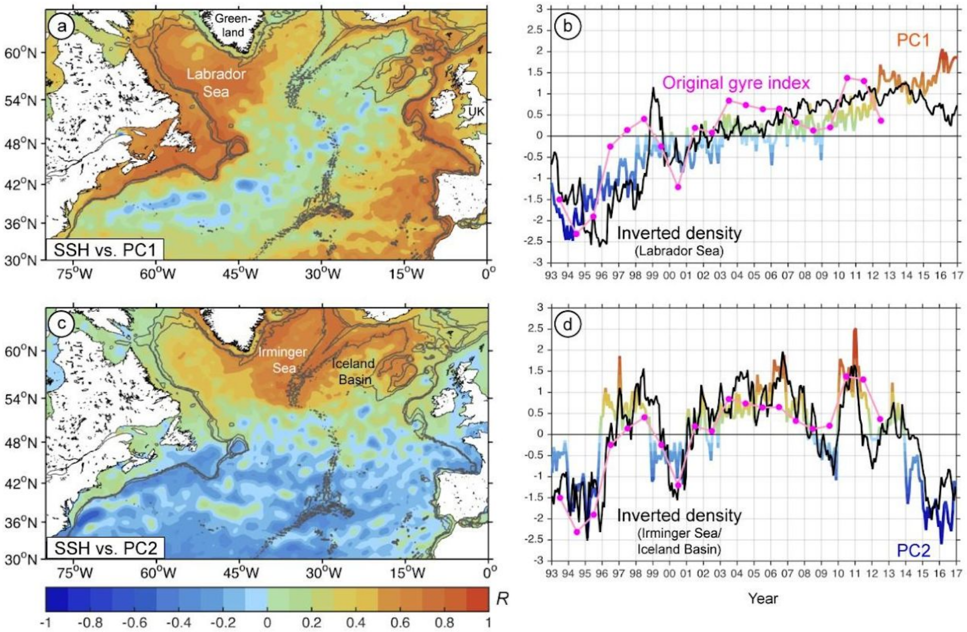

Figure 12: The two leading EOF modes derived from the *DUACS 2014* altimetry data set (1993–2016). (a) Correlations between the first principal component (PC1) and the SSH field; (b) PC1 (coloured), the inverted deep Labrador Sea density anomaly ($\sigma 2$ averaged over the 1000–2500-m layer in the Labrador Sea; black); (c) correlations between PC2 and the SSH field; and (d) PC2 (coloured) and the inverted density anomaly ($\sigma 1$ averaged over the top 1000-m layer in the vicinity of the Reykjanes ridge; black). The original gyre index (from Larsen et al. (2012), annual averages, pink) is added to (b) and (d). None of the time series are to scale. For the domain included, EOF1 and EOF2 explain 18.5 and 7%, respectively, of the total variance. An analysis based on a re-mapped coarser resolution (1° latitude × 1° longitude) SSH data set gave a very similar result. **From Hátún and Chafik, 2018.**

The subpolar gyre regulates silicate concentrations in the North Atlantic

Hátún *et al.*, 2017. Scientific Reports volume 7, Article number: 14576. Journal Impact Factor 4.011

[HAV, SAMS] The North Atlantic spring bloom, which is the primary food supplier to marine ecosystems in these subpolar waters, is terminated by silicate limitation every spring/summer. Hátún *et al.* (2017) show, from a new comprehensive compilation of data from the subpolar Atlantic Ocean, clear evidence of a marked pre-bloom silicate decline of 1.5–2 µM throughout the winter mixed layer during the last 25 years (Figure 13). This silicate decrease is primarily attributed to natural multi-decadal variability through decreased winter convection depths since the mid-1990s, a weakening and retraction of the subpolar gyre and an associated increased influence of nutrient-poor water of subtropical origin. These marked fluctuations in pre-bloom silicate inventories will likely have important consequences for the spatial and temporal extent of diatom blooms, thus impacting ecosystem productivity and ocean-atmosphere climate dynamics.

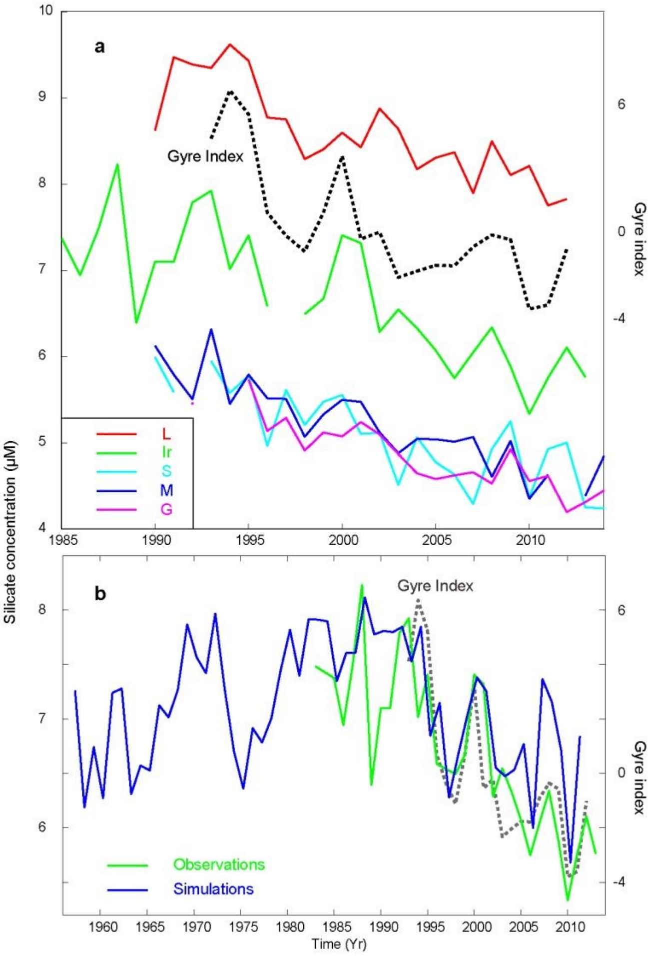

Figure 13: Temporal evolution of key parameters. (**a**) Coloured lines show pre-bloom upper ocean silicate concentrations across the subpolar Atlantic; L (Labrador Sea), Ir (Irminger Sea), S (Svinøy Section), M (Ocean Weather Ship M) and G (Gimsøy Section). The samples are made in the pre-bloom homogeneous winter mixed layer, and thus represent several hundred meters in the Nordic Seas and typically more than a kilometre in the Labrador Sea. The dashed black line shows the unitless gyre index, associated with the leading North Atlantic sea-surface height mode, as obtained from altimetry observations. (**b**) Similar to (**a**) but showing the silicate concentrations in the northern Irminger Sea for a longer time period. The observations are in green, simulations (0–200 m, March) in blue and the gyre index in dashed grey. **From Hátún *et al*., 2017.**

As a continuation of this work, we have also reviewed the fertilizing silicate fluxes from the large subpolar gyre source, across the major oceanic subarctic front and further across shelf edge and tidal fronts and onto adjacent shelves (Hátún *et al*., 2019, In Review). As a case study, we illustrate potential linkages between the open ocean dynamics and the primary production, fish larvae abundances and seabird breeding success within the Faroe shelf ecosystem. The 'boosting effect' of vigorous winter convection which takes place every 5-8 years - recently by the intensified convection during the winters 2013-2016 - is discussed in Jacobsen *et al*. (2019).

Mechanisms of the mid 2000s cooling in the subpolar gyre.

Herbaut, Houssais *et al*., in preparation.

[CNRS] The North Atlantic Ocean is characterized by a multidecadal mode of variability of the upper ocean heat content (Ruiz-Barradas *et al*. 2018). After a warming and salinification period started in the mid 1990's, the eastern subpolar gyre (ESPG) has experienced a cooling trend since the mid 2000's (Robson *et al*., 2016, Piecuch *et al*. 2017). Robson *et al*. (2016) explained this cooling by the decrease of the meridional overturning circulation, although wind driven changes in the gyre circulation could also be involved (Piecuch *et al*., 2017). Within D2.2 we want to evaluate the role of the atmospheric forcing with respect to the oceanic conditions prevailing at the end of the 1990s on the formation of the 2000s cooling of SPG. The analysis was based on numerical simulations of a ¼° regional model in particular on sensitivity experiments to atmospheric forcing and the initial oceanic state. The experiments showed that the cooling was not simultaneous over the SPG, it started in the western part of the North Atlantic Current (NAC) then extended to its eastern part, before reaching the Iceland Basin (Figure 14). It was accompanied by a shift of the NAC at the beginning of the 2000s. The changes in the heat content cannot be linked to variations of the MOC or changes in the gyre strength but are rather associated with changes in the Labrador Sea Water pathway around the gyre.

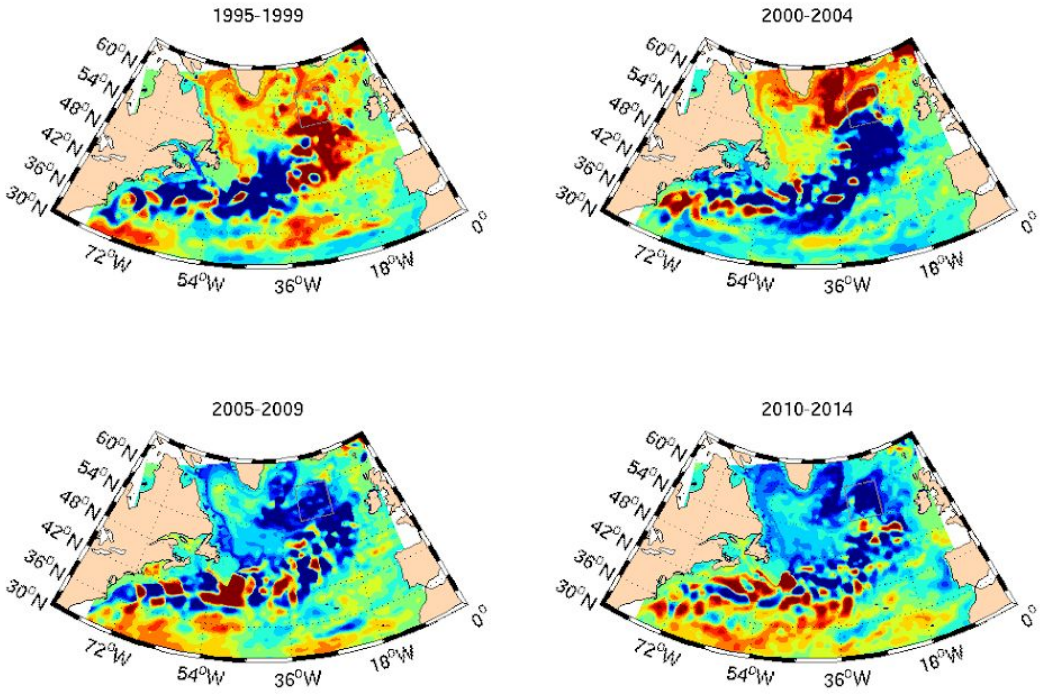

Figure 14: Trends in the upper 500 meter ocean heat content computed over 5-year periods in the simulation.

Insights into Decadal North Atlantic Sea Surface Temperature and Ocean Heat Content Variability from an Eddy-Permitting Coupled Climate Model

Moat *et al*. 2019. Journal of Climate 32(18). Journal Impact Factor 4.805

This work developed a novel combined approach to the mixed layer and full-depth ocean heat budgets and used it to investigate sea surface temperature (SST) and ocean heat content (OHC) variability on decadal to multi-decadal time scales in the subpolar North Atlantic (SPNA), the main centre of action of the Atlantic multi-decadal variability (AMV). Our analysis has employed a state-of-the-art coupled climate model, HadGEM3-GC2, in which the simulated AMV index and spatial pattern is very similar to observed estimates. The new elements of the approach are development of an equation for evolution of anomalous SST and a parameterization of the diffusive heat flux at the base of the mixed layer. The results of our analysis show that both OHC and SST tendencies are the result of a competition between two terms representing the effects of surface fluxes and advection for OHC (advection-entrainment for SST). These terms have different forms in the OHC and SST equations, because additional terms related to entrainment appear in the SST equation but not in the OHC equation. Hence, the relationship between OHC and SST becomes an investigation into how and why the surface fluxes and advection-related terms differ between the OHC and SST equations. The main conclusions are:

- Anomalies in the OHC tendency propagate around the SPNA on decadal time scales with a clear relationship to the phase of the AMOC.
- In the SPNA, AMOC anomalies lead SST anomalies, which in turn lead OHC anomalies. This result does not depend on the depth used for calculation of OHC and is common to both eastern and western SPNA.
- OHC variations in the SPNA on decadal time scales are largely dominated by AMOC variability because it controls variability of advection which is shown to be the dominant term in the OHC budget. Surface heat fluxes modulate the OHC variability, particularly as OHC peaks and declines. Surface heat flux plays a larger role in SST variability.
- The advection term covaries with the AMOC in the eastern SPNA but lags the AMOC in the western SPNA, leading to the anticlockwise propagation of OHC anomalies around the SPNA.
- The lag between OHC and SST is traced to differences between the advection term for OHC and the advection-entrainment term for SST. The latter leads the former particularly in the western SPNA.
- In the western SPNA, surface fluxes and SST appear to precede and cause AMOC changes, whereas in the east AMOC changes cause the changes in SST and surface fluxes.

The main implication of our study is that deep OHC changes are not associated with immediate changes in SST in HadGEM3-GC2; indeed, changes in SST precede OHC deep changes. There is also a very clear difference in the dominant process between the eastern and western SPNA. In the former region, advection is dominant, whereas in the latter surface fluxes dominate. While our study confirms the important role of the AMOC in the decadal variability of the North Atlantic SST, this role cannot be simplified as an increasing AMOC leading to increasing heat content leading to increasing SST, which is a common assumption underlying numerous studies of contemporary and paleo variability of the North Atlantic (e.g., Chen and Tung 2018). On the other hand, the SST can and does begin rising quite soon after the AMOC starts increasing, because the surface flux term is already driving an increasing SST at this time and reduced opposition to this term from advection reinforces this trend. In the western SPNA in particular it seems that surface fluxes drive both the subsequent evolution of the advection-entrainment term, and ultimately the AMOC. The detailed mechanism by which surface fluxes can influence the advection still need to be determined but may be related to the projection of short (seasonal to interannual) time scale correlations between MLD and temperature onto the decadal time.

Heat and freshwater transports

OSNAP mooring time series and hydrographic sections

Lozier et al. 2019 and Holliday et al. 2018

[SAMS, NERC, NIOZ, GEOMAR, CNRS] Meridional heat and freshwater transports across the OSNAP line have been calculated for the OSNAP mooring time series (Lozier *et al.* 2019) and for the hydrographic sections of summer 2014 and 2016 (Holliday *et al.* 2018). The results from the two methods have some similarities and some differences, which are worth exploring

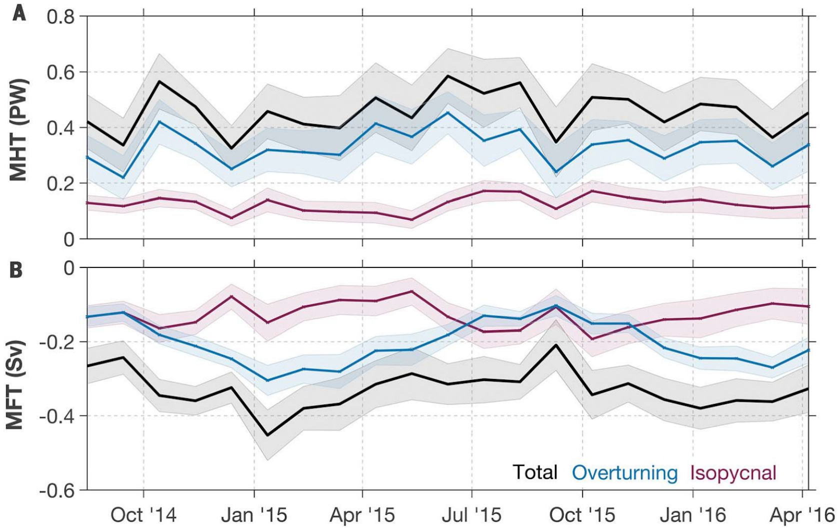

Figure 15: MHT and MFT across the OSNAP section. **(A)** Total MHT. **(B)** Total MFT relative to the 21-month section mean salinity of 34.92 across the full OSNAP section during the period of August 2014 to April 2016 (black lines). Both transports are decomposed into overturning and isopycnal components (blue and red lines, respectively). Shading indicates uncertainty in the 30-day mean estimates. **Taken from Lozier *et al.* (2019).**

Both studies decompose the heat and freshwater transports into overturning and isopycnal components, the heat and freshwater transports are partitioned into the following: (i) that which is accomplished by warm (fresh) water moving northward in the upper limb and (salty) cold water moving southward in the lower limb (the overturning component) and (ii) that which is accomplished by opposing northward and southward flows (i.e., carrying waters with different T/S properties) on the same isopycnal (the isopycnal transport component).

Lozier *et al.* (2019) for the OSNAP mooring time series produce an estimate of MHT across the entire OSNAP section of 0.45 ± 0.02 PW. The record is marked by strong temporal variability (Figure 15A), with a range of 0.33 to 0.59 PW. This variability is largely determined by the variable flow field rather than by temperature fluctuations: velocity variance explains 93% of the MHT variance. Decomposition reveals that the overturning component dominates the total MHT, accounting for 73% of the mean and 87% of the variance.

The mean MFT across the entire OSNAP section is estimated at −0.33 ± 0.01 Sv. The MFT time series also reveals strong temporal variability (Figure 15B), with a range of −0.45 to −0.21 Sv. As with MHT, the majority of the MFT variance is explained by the variable flow field: velocity variability (rather than salinity variability) explains 78% of the total MFT variance. From the decomposition, we find that, on average, overturning accounts for 62% of the total freshwater transport across the full OSNAP array. However, there is considerable range in that partitioning, and there is a period of time (July to November of 2015) when the isopycnal component is larger. During this time period, the net southward flux of fresh water due to opposing flows on isopycnals is larger than the net southward freshwater flux accomplished by the overturning.

Note the similar (though inverted) variability signal of isopycnal components of MHT and MFT in Figure 15. This is because the temperature and salinity on isopycnals must be coupled—warmer + saltier/cooler + fresher. The variability in the overturning component of MHT this looks very similar to the total MHT (dominated by volume transport). But for the MFT, the overturning component appears to be dominated by an annual cycle unrelated to the volume transport. This implies an annual cycle of freshening/salinification in the overturning circulation, though the time series at present is too short to make robust conclusions about an annual cycle.

Table 1:Estimates of Overturning Circulation, Isopycnal Circulation and Heat and Freshwater Transport With Uncertainties. **Taken from Holliday et al 2018.**

Parameter	**OS2014**	**OS2016**
$\text{AMOC}_{\sigma\text{-max}}$	20.6 ± 4.7 Sv	10.6 ± 4.3 Sv
$\text{AMOC}_{\sigma\text{-}n}$	23.3 ± 4.7 Sv	13.0 ± 4.3 Sv
Maximum isopycnal transport	−41.4 ± 8.2 Sv	−58.6 ± 7.4 Sv
Total heat flux (HT)	0.39 ± 0.08 PW	0.32 ± 0.13 PW
Isopycnal heat transport (HT_{gyre})	0.17 ± 0.02 PW	0.21 ± 0.02 PW
Total freshwater flux at section (FT)	−0.21 ± 0.03 Sv	−0.25 ± 0.08 Sv
Isopycnal freshwater transport (FT_{gyre})	−0.10 ± 0.02 Sv	−0.16 ± 0.03 Sv

The MFT and MHT estimates of Holliday *et al.* (2018) are summarised in Table 1. The total heat and freshwater fluxes both appear slightly low compared to those from the mooring arrays, above, but are within the estimated uncertainty. However, in contrast to results from the mooring arrays, up to 65% of both the heat and freshwater transport was carried by the isopycnal circulation, with isopycnal property transport highest in the western Labrador Sea and the eastern basins (Iceland Basin to Scotland). These differences will be explored in future work, partitioning the MHT and MFT components across both OSNAP East and West and examining further years of OSNAP mooring data.

Main results achieved

The fundamental aim of this Blue-Action deliverable is to investigate the propagation of warm ocean waters from the subpolar gyre over the GSR and towards the Arctic. As stated earlier, we have hints that we are on the cusp of a revolution in decadal climate predictability, with the revolution driven by comprehensive observations of the subpolar North Atlantic. Major components of the subpolar North Atlantic observing system are beginning to return results, and Blue-Action has contributed to the collection and analysis of these data. Perhaps foremost among these is the Overturning in the Subpolar North Atlantic Program (OSNAP) launched in the summer of 2014.

> "A sea change in our view of overturning
> in the subpolar North Atlantic."

The first 21-month record of OSNAP, coupled with Argo float data, reveal (Lozier et al 2019):

- A highly variable overturning circulation (MOC)
- The conversion of warm, salty, shallow Atlantic waters into colder, fresher, deep waters that move southward in the Irminger and Iceland basins is largely responsible for overturning and its variability in the subpolar basin. This is a departure from the prevailing view that changes in deep water formation in the Labrador Sea dominate MOC variability
- The majority of the heat and freshwater transport across the OSNAP line, and its variability, is due to the variable overturning circulation rather than variations in temperature and salinity
- Transports (and variability of transports) of heat northwards in the upper limb of the MOC are dominated by transports east of Reykjanes Ridge/Iceland Basin.

The early stage of these observations is highlighted by differences in transport estimates across the OSNAP line between mooring/Argo data (Lozier *et al.,* 2019) and CTD/LADCP data sections from the start and end of the mooring time series (Holliday *et al.,* 2018). While overall MOC, heat and freshwater transports are similar, Holliday *et al.* (2019) find a significantly larger contribution to the MOC from the Labrador Sea (particularly in 2014). Holliday *et al.* (2018) also find a larger contribution to heat and freshwater transports from the isopycnal circulation (up to 65%) as against the overturning circulation. As the Labrador Sea also dominates the isopycnal circulation, closer examination of the Labrador Sea circulation calculations is required to find the source of these differences.

Examination of transports across the OSNAP line has highlighted the important role of heat and volume transport in the eastern North Atlantic in the basin-scale meridional transports. Ongoing glider deployments from SAMS (Houpert *et al.,* 2018; Gary *et al.*, 2018) across the Rockall Trough and Hatton-Rockall plateau have made considerable progress in characterising the volume transports and seasonal variability within the North Atlantic Current branches in the Eastern Subpolar Gyre. Gary *et al.* (2018) find a weak seasonal signal with the weakest transports occurring in summer in the Rockall Trough, consistent with seasonal changes in the regional-scale wind stress curl. Houpert *et al.* (2018) find possibly slightly stronger northward transports over Rockall-Hatton plateau in the summer months, with winter transports more variable. Though more winter glider transects are required to confirm these results.

Further north, structure and forcing of observed exchanges across the Greenland–Scotland Ridge are further examined by Bringedal *et al*. (2018). They conclude that the observed variable exchanges across the Greenland– Scotland Ridge largely reflect an overturning circulation on interannual time scales with a weaker horizontal circulation in the Nordic seas on seasonal time scale. Considering buoyancy effects was found to be essential for the interannual time scales but not for the seasonal variability. The barotropic-like seasonal cycle of anomalous inflow and overflow following the rim of the Nordic seas can be explained by the direct influence of wind associated with changes in sea level pressure, similarly to the conclusions of Gary *et al. (*2017) for the seasonal cycle in the Rockall Trough.

Østerhus *et al*. (2019) have constructed a consistent volume budget for the Arctic Mediterranean seas (AM) from observations of the major inflows and outflows over two decades. Exchanges with the subpolar North Atlantic suggest overturning circulation at the Greenland-Scotland Ridge (GSR) of 8.0 Sv. This compares to the mean estimate of 15.6 Sv at $\text{OSNAP}_{\text{east}}$. These suggest that over 7 Sv (> 45%) of MOC overturning measured at the OSNAP line is driven by processes occurring in the northeast section of the subpolar gyre between the OSNAP line and the GSR (Irminger Sea and Iceland Basin). No significant trends in volume exchanges between the North Atlantic and AM were found although the authors pinpoint an extreme lack of coverage for the surface outflow through the Denmark Strait, the overflow across the Iceland–Faroe Ridge, and the inflow over the Scottish shelf. On a more local scale, but important to avoid double counting in GSR overflow budgets, Hansen *et al.* (2017) found no evidence for the Southern Faroe Current circulating the Faroe Plateau.

Within Blue-Action, there has been detailed study of spatial and temporal variability and causes of Irminger Sea deep convection. Inter-comparison of deep convection between three different ocean observing platforms in the Irminger Sea (de Jong *et al* 2018) showed maximum mixed layer depths reached during the strong winter of 2014-15 were nearly identical at the different sites even though the onset and evolution were significantly different. Deep convection onset and evolution differed due to preconditioning and cold inflow from the south. While more intermittent warm events (eddies) disrupted the formation of mixed layer depths in the north. This shows the deep convection to be a result of a complex interaction of local atmospheric processes and more remote ocean processes of inflow and eddies.

> "...the main source of multi-winter variability in Irminger Sea deep convection is shown to be changes in the frequency of Greenland tip jets..."

Measurements from surface moorings in the Irminger Sea reveal strong variability due primarily to variations in frequency of intense short timescale (1–3 days) forcing. Combining the observations with ECMWF atmospheric reanalysis (ERA5), the main source of multi-winter variability is shown to be changes in the frequency of Greenland tip. A new picture of tip jet formation, and Irminger Sea deep convection, has been developed recognizing the importance of the East Atlantic Pattern (EAP). A positive NAO only results in strong Irminger Sea heat loss when not dominated by the EAP, as the latter leads to northerly flow and tip jet suppression. The strong multi-winter variability in Irminger Sea heat loss observed has implications for dense water formation at the headwaters of the Atlantic overturning circulation. Improved representation of this coupled process in ocean-atmosphere models, including its complex relationship with the two main modes of North Atlantic atmospheric variability, may prove key to obtaining reliable projections of future changes in both the overturning and climate.

Perhaps fundamentally for subpolar gyre studies, Hátún and Chafik (2018) examine the recent ambiguity of the North Atlantic Subpolar Gyre Index. Updates to the SPGI including the most recent data produce a first principal component (PC1) that has less sub-decadal variability than the original gyre index and a spatial pattern that resembles the shape of the SPG less closely. The EOF analysis now segregates the trend-like and the inter-annual variability into two separate components. PC1 represents the gradual changes in the deep dense mode waters in the Labrador Sea, the western side of the Irminger Sea, and the continental margins. PC2 is linked to marine climate in the highly energetic, changeable, and biologically productive waters between Greenland and the Rockall Plateau, and to the Gulf Stream/subtropical gyre region.

> "Our recommendation to the oceanographic community is to carefully
> use PC1 and/or PC2 depending on the region of interest and research question."

Inter-annual to decadal variability

The observational time-series which form the basis of much of the work reported here are still relatively short (just two years of OSNAP overturning and transport estimates were available for this report though more will be available before the end of Blue-Action), but combination with modelling results (Moat *et al*. 2019 and Herbaut *et al.*, in preparation) allows us to examine longer-term changes.

Herbaut *et al. (in prep.)* evaluate the role of the atmospheric forcing with respect to the oceanic conditions prevailing at the end of the 1990s on the formation of the 2000s cooling of SPG. They show that the cooling was not simultaneous over the SPG, starting in the western part of the North Atlantic Current (NAC) then extended to its eastern part, before reaching the Iceland Basin. It was accompanied by a shift of the NAC at the beginning of the 2000s. The changes in the heat content cannot be linked to variations of the MOC or changes in the gyre strength but are rather associated with changes in the Labrador Sea Water pathway around the gyre. In contrast, Moat *et al.* (2019) examining a much longer climate model period over many decades, find anomalies in the heat content (OHC) tendency propagate around the subpolar North Atlantic on decadal time scales with a clear relationship to the phase of the AMOC. OHC variations on decadal time scales are largely dominated by AMOC variability because it controls variability of advection which is shown to be the dominant term in the OHC budget. In the western SPNA, surface fluxes and SST appear to precede and cause AMOC changes, whereas in the east AMOC changes cause the changes in SST and surface fluxes.

Inter-annual to decadal-scale variability is also visible in biogeochemical tracers. The North Atlantic spring bloom, the primary food supplier in these subpolar waters, is terminated by silicate limitation every spring/summer. Hátún *et al*. (2017) show clear evidence of a marked pre-bloom silicate decline throughout the winter mixed layer during the last 25 years. This is primarily attributed to decreased winter convection depths, a weakening and retraction of the subpolar gyre and an associated increased influence of nutrient-poor water of subtropical origin. These marked fluctuations in pre-bloom silicate inventories will likely have important consequences for the spatial and temporal extent of diatom blooms, thus impacting ecosystem productivity and ocean-atmosphere climate dynamics.

New research (Holliday *et al.*, in review, not reported in detail here) show that the eastern subpolar North Atlantic underwent extreme freshening during 2012 to 2016, with a magnitude never seen before in 120 years of surface measurements. The cause was unusual regional winter wind patterns driving major changes in ocean circulation, including slowing of the North Atlantic Current and diversion of Arctic freshwater from the western boundary into the eastern basins. We find that wind-driven routing of Arctic-origin freshwater intimately links conditions on the North West Atlantic shelf and slope region with the eastern subpolar basins. This reveals the importance of atmospheric forcing of intra-basin circulation in determining the salinity of the subpolar North Atlantic. The freshwater anomaly in the Iceland Basin is now propagating into the Irminger and Labrador Seas along the pathway of the subpolar circulation, and into the Nordic Seas. Historical salinity anomalies have taken 4-6 years to propagate from 50°N, 30°W to Svalbard, so we might expect the Atlantic Waters there to be freshening from 2018 onwards. Changes in salinity and stratification impact the extent of deep convection and contribute to density changes in the overflow waters and the subpolar deep western boundary currents and hence the MOC; results from Lozier *et al.* (2019) and dynamical arguments suggest that MOC changes may be driven more by the interaction of these anomalies with the eastern. Examination of OSNAP and Greenland-Scotland ridge overflow timeseries over the coming years should help elucidate the contributions of these multi-year processes. The far-reaching impact of eastern Atlantic salinity anomalies highlights the importance of understanding, and correctly simulating, interactions between the North Atlantic Ocean dynamics and the atmosphere circulation for future climate predictions.

Progress beyond the state of the art

Numerous CGCM experiments where AMOC anomalies are initialized in the subpolar gyre, have demonstrated greatly enhanced multidecadal predictability. It is our goal to step beyond the initialization of AMOC anomalies, but also to predict those anomalies themselves. This could be possible because AMOC anomalies are a lagged response to buoyancy forcing at high latitudes connecting the AMOC upper and lower limbs. Recent observations supported by Blue-Action and reported here have produced a paradigm shift in our understanding of this connection both in the large-scale circulation and in the processes of varying modes of atmospheric circulation directly impacting subpolar gyre deep winter mixing. We here show, from the first results of mooring arrays across the subpolar North Atlantic, that processes in the eastern subpolar gyre are of paramount importance in overturning.

On multi-year to decadal scales, Blue-Action supported climate modelling shows heat anomalies propagating anticlockwise around the subpolar gyre, with sea surface temperature variability clearly leading AMOC variability. A very recent analysis of the adjoint ECCO model was able to reconstruct 50% of subpolar AMOC variance using the adjoint sensitivities with knowledge of sea surface temperature and salinity for the preceding two to three years (Helen Johnson, pers. comm.).

Monitoring of the important processes in the eastern subpolar gyre – an area with little coverage from Argo floats – has advanced significantly with the use of gliders launched from SAMS along the OSNAP east section and innovative processing methods, using this data to explore seasonal cycles of the major northward near-surface flows which appear to drive AMOC variability.

As well as the paramount importance of the eastern subpolar gyre in overturning, observations monitoring flows across the OSNAP section and across the Greenland-Scotland ridge demonstrate the importance of processes in the subpolar North Atlantic, between the OSNAP line and the GSR, to the overturning. About half of the lighter waters travelling northwards across the OSNAP line return south as denser water without ever crossing the GSR. Strong cooling events in this region have been revealed using measurements from the Ocean Observatories Initiative Irminger Sea surface mooring, showing changes in the frequency of Greenland tip jets that can result in hourly mean heat loss exceeding 800 W m^{-2}.

As part of a suite of large national and international studies targeting subpolar North Atlantic circulation (OSNAP, AtlantOS, NACLIM, NERC CLASS, OVIDE…) Blue-Action has made significant contribution to assessing and quantifying subpolar gyre circulation and the atmospheric and oceanic mechanisms influencing it variability. OSNAP observations have demonstrated the dominant role played by the Arctic Mediterranean seas and the seas between the GSR and OSNAP -- rather than Labrador Sea deep convection -- in the MOC linking the warm and saline eastern waters with the colder and less saline western waters. In addition to OSNAP observations, regional studies across the Rockall Trough/Rockall-Hatton Bank, over the GSR and in the Irminger Sea have begun to quantify the volume, heat and freshwater transports, variability and controlling mechanisms. Further integrated model-observation studies are underway to advance our understanding of the mechanisms involved.

Thus, we are entering a period when comprehensive observations of the subpolar North Atlantic are driving a revolution in understanding of the processes and mechanisms of subpolar gyre circulation and propagation of heat and freshwater anomalies on seasonal to decadal timescales. These advances will in turn drive improved decadal climate predictability.

Impact

<u>How</u> has this work contributed to the expected impacts of Blue-Action?

The work described here contributes to improving the capacity to predict the weather and climate of the Northern Hemisphere both through the development of new, optimized data products and improved understanding of Arctic-lower latitude linkages. Hydrographic data from the OSNAP moorings array and associated CTD/LADCP sections, combined in innovative ways with glider data in the east, Argo floats and hydrographic models on the ocean boundaries, give us the first detailed time series of meridional overturning, heat and freshwater transports across the width of the subpolar North Atlantic. The two-year time series presented here should be extended to 4-6 years by the end of Blue-Action.

Through optimizing the flux estimates from moored ocean observing, identifying gaps and developing new algorithms, the work reported here makes extensive use of Earth observation assets and points towards future use. The OSNAP array heat transport estimates make use of Earth observations from space in combining measurements from moorings in the important basin boundary regions with satellite tracked Argo float data in the interior. The critical eastern North Atlantic region is increasingly being monitored using glider-based measurements, directed remotely via satellite, developing new algorithms for combining these data with more conventional datasets.

The improved understanding of the processes driving the variability of AMOC and ocean heat transport in the subpolar North Atlantic on seasonal to decadal scales, particularly emerging knowledge of relationships of AMOC with SST on multi-year timescales will feed into improved capacity to predict Northern hemisphere weather on these timescales.

Impact on the business sector

Improved understanding, and associated improved predictability, of the subpolar North Atlantic feeds directly into the ability to predict distributions of commercially important fish stocks. Within Blue-Action, Mark Payne (DTU, Denmark) demonstrates the strong linkages between for example blue whiting distribution in the eastern North Atlantic and the warmth and salinity of waters in the region (http://fishforecasts.dtu.dk).

Hátún *et al.,* (2019, In Review) have also reviewed the fertilizing silicate fluxes from the large subpolar gyre source, across the major oceanic subarctic front and further across shelf edge and tidal fronts and onto adjacent shelves. They illustrate potential linkages between the open ocean dynamics and the primary production, fish larvae abundances and seabird breeding success within the Faroe shelf ecosystem.

Lessons learned and Links built

- The work carried out in this deliverable links to completed Blue-Action deliverables D2.5 “Assessment of oceanic anomalies of predictive potential” and D2.6 “Oceanic heat anomalies and Arctic sea-ice variability”. It also has close links to deliverables in preparation: D2.1 “Model-observation and reanalyses comparison at key locations for heat transport to the Arctic” and D2.3 “Processes and flow over the Iceland-Faroe ridge”. These deliverables will be available in Zenodo: https://zenodo.org/communities/blue-actionh2020
- H2020 projects Blue-Action and Atlas ran a joint workshop “Workshop on the subpolar North Atlantic eastern boundary”, Edinburgh, 14 October 2019. This workshop promoted closer collaboration between the groups making (especially moored) observations along the eastern boundary of the subpolar North Atlantic. As a clustering activity between Blue-Action, Atlas and others, with extended funding for NOAC and OSNAP recently secured, the A4 project in Ireland funded, and new announcements of opportunity associated with OSNAP in the UK, this workshop was timely and fruitful.
- 16 October 2019 Blue-Action held a societal engagement meeting at Edinburgh City Chambers: “Blue-Action: Ocean predictions and observations in response to the climate emergency” including contributions from D2.2 co-authors Stuart Cunningham (SAMS) and Bee Berx (MSS). This was a well-attended event with a wide range of stakeholders and academics present.

Contribution to the top level objectives of Blue-Action

Objective 2 Enhancing the predictive capacity beyond seasons in the Arctic and over the Northern Hemisphere

The North Atlantic is the region of the globe where models demonstrate the best predictive skill on the difficult medium-range seasonal-to-decadal timescales. Numerous experiments where AMOC anomalies are initialized in the subpolar gyre, have demonstrated greatly enhanced predictability. This skill is predicated on the ‘memory’ of the subpolar North Atlantic for anomalies of heat content and surface temperature. Our goal to step beyond the initialization of AMOC anomalies and to predict those anomalies themselves. This revolution will be driven by comprehensive observations of the subpolar North Atlantic.

The observational results reported here contribute to a step-change in the understanding of subpolar North Atlantic circulation, ocean processes and forcing mechanisms. D2.2 scientists and science have contributed substantially to increased understanding of the dominant role of the eastern subpolar North Atlantic in the seasonal to decadal variability of the meridional overturning circulation and northward transport of heat in the ocean, and of the regions of the subpolar ocean critical for ocean-atmosphere exchanges. This knowledge feeds directly into Blue-Action Objective 2

Objective 5 Optimizing observational systems for predictions

With extended funding for NOAC and OSNAP recently secured, the A4 project in Ireland, the increased understanding of the dominant role of the eastern North Atlantic in AMOC and northward heat transport in the ocean described in this report is feeding into the design of mooring arrays along the eastern boundary of the subpolar North Atlantic.

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Dissemination and exploitation of Blue-Action results

Dissemination activities

Type of dissemination activity	Name of the scientist (institution), title of the presentation, event	Place and date of the event	Type of Audience	Estimated number of persons reached	Link to Zenodo upload
Participation to an event other than a conference or workshop	de Jong, M.F. (NIOZ), Science Encounters Art Texel, Outreach/Collaboration with artists	Texel (NL), 1 June - 31 August 2019	General Audience	200	
Participation to a conference	de Jong, M.F. (NIOZ), L. de Steur, K. van der Laan. Transports through the OSNAP Irminger Current array. Ocean Sciences Meeting 2018	Portland (USA), 11-16 February 2019	Scientific Community (higher education, Research)	200	https://www.zenodo.org/communities/blue-actionh2020
Participation to a conference	de Jong, M.F. (NIOZ) Recent strengthening of deep convection in the North Atlantic Subpolar Gyre. Joint Assembly IAPSO-IAMAS-IAGA	Cape Town (SA), 27 August-1 September 2017	Scientific Community (higher education, Research)	150	https://www.zenodo.org/communities/blue-actionh2020
Organisation of a workshop	de Jong, M.F. (NIOZ), L. de Steur, M. Oltmanns, and J. Karstensen. NIOZ Irminger Sea moorings and comparison between LOCO, CIS and OOI. Irminger Sea OOI workshop	Southampton (UK), 8-9 November 2017	Scientific Community (higher education, Research)	30	https://www.zenodo.org/communities/blue-actionh2020
Participation to a conference	de Jong, M.F. (NIOZ), L. de Steur, and S. Kritsotalakis. Volume, heat and freshwater transport in the Irminger Current. EGU General Assembly	Vienna (AU), 23-28 April 2017	Scientific Community (higher education, Research)	150	https://www.zenodo.org/communities/blue-actionh2020
Participation to a conference	Hjálmar Hátún (HAV). The subpolar gyre regulates silicate concentrations in the North Atlantic, AGU 2018 OSM	Portland (US), 11-16 February 2018	Scientific Community (higher education, Research)	100	https://doi.org/10.5281/zenodo.1295928
Participation to a conference	Hjálmar Hátún (HAV). Winter convection blows life - A Bird's-eye view, Seabird Conference.	Reykjavik (IS), 22-23 March 2017	Scientific Community (higher education, Research)	50	https://doi.org/10.5281/zenodo.1295952

Participation to a workshop	Hjálmar Hátún (HAV). The productive Irminger Sea, Irminger Sea Workshop.	Southampton (UK), 9-10 November 2017	Scientific Community (higher education, Research)	35	https://doi.org/10.5281/zenodo.1295966
Participation to a conference	Hjálmar Hátún (HAV). Selected short stories from Icelandic waters, Biology Conference.	Reykjavik (IS), 26-28 October 2017	Scientific Community (higher education, Research)	500	https://doi.org/10.5281/zenodo.1295411
Participation to a conference	Hjálmar Hátún (HAV). The subpolar gyre regulates the pelagic complex	Bergen (NO), 16-18 November 2018	Scientific Community (higher education, Research)	60	https://doi.org/10.5281/zenodo.3459089
Participation to a conference	Hjálmar Hátún (HAV). The Subpolar Gyre regulates ecosystems in the North Atlantic Ocean, 2019 Geodynamics Seminar Series	WHOI (US), 22-24 April 2019	Scientific Community (higher education, Research)	120	https://doi.org/10.5281/zenodo.3459097
Press release	Stuart Cunningham (SAMS): The Atlantic's Role in European Climate	Thursday 31/1/19 (SAMS website): https://www.sams.ac.uk/news/sams-news-osnap-discovery-of-amoc-influence.html	Public		https://www.zenodo.org/communities/blue-actionh2020
Participation to a workshop	Laura de Steur (NIOZ), Results from the NIOZ Irminger Sea moorings and a comparison of LOCO, CIS and OOI. Irminger Sea Workshop (NOC)	Southampton (UK), 8-9 Nov 2017	Scientific Community (higher education, Research)	35	https://doi.org/10.5281/zenodo.1283847
Participation to a conference	Stuart Cunningham (SAMS) presentation " Circulation in the Eastern subpolar North Atlantic Based on Three Years of Mooring Measurements"	Vienna (AT), 8-13 April 2018	Scientific Community (higher education, Research)	>500	https://doi.org/10.5281/zenodo.1284302
Participation to a conference	Stuart Cunningham (SAMS). NERC Climate Linked Atlantic Sector Science Kick-Off Meeting	NOC, Southampton (UK), 10 May 2018	Scientific Community (higher education, Research)	100	http://doi.org/10.5281/zenodo.1284234
Participation to a conference	Gerard McCarthy (NUIM). The Blue Action Project, H2020 ARICE Kick Off meeting	ARICE Kick Off meeting, Bremerhaven (DE), 6-8 February 2018	Scientific Community (higher education, Research)	100	https://doi.org/10.5281/zenodo.1284332

Participation to a conference	Gerard McCarthy (NUIM). Drivers of quasi- and multi-decadal Atlantic Variability, EGU 2018	Vienna (AT), 8-13 April 2018	Scientific Community (higher education, Research)	500	https://doi.org/10.5281/zenodo.1284353
Participation to a workshop	Karin Margretha H. Larsen (HAV). Faroese Observations and Blue-Action (WP2), YOPP workshop	Reading (UK), 5-6 September 2016	Scientific Community (higher education, Research)	30	https://doi.org/10.5281/zenodo.1283167
Participation to a conference	Karin Margretha H. Larsen (HAV). Monitoring One of the Tipping Points of the AMOC, AGU 2018 OSM	Portland (US), 11-16 February 2018	Scientific Community (higher education, Research)	>500	https://doi.org/10.5281/zenodo.1188871
Participation to a workshop	Ben Moat (NOC), presentation on "Evaluating North Atlantic Ocean circulation and properties, Evaluating climate and Earth System models at the process level" at the EC Workshop Evaluating climate and Earth system models at the process level	Brussels (BE), 23-24 May 2017	Scientific Community (higher education, Research)	30	https://doi.org/10.5281/zenodo.1248523
Participation to a conference	Ben Moat (NOC), Relationship between changes in the AMOC and North Atlantic sea surface temperature, ACSIS Ocean-Ice Theme Science Day	NOC, Southampton (UK), 27th April 2018	Scientific Community (higher education, Research)	20	https://doi.org/10.5281/zenodo.1248516
Participation to a conference	Ben Moat (NOC), Transport of freshwater and heat in the subtropical North Atlantic, Understanding Change and Variability in the North Atlantic Climate System, ACSIS - OSNAP - RAPID Joint Science Meeting	Oxford (UK), 19-21 September 2017	Scientific Community (higher education, Research)	100	https://doi.org/10.5281/zenodo.1248505
Participation to a conference	Ben Moat (NOC), Relationship between changes in the AMOC, North Atlantic heat content and SST., Understanding Change and Variability in the North Atlantic Climate System, ACSIS - OSNAP - RAPID Joint Science Meeting	Oxford (UK), 19-21 September 2017	Scientific Community (higher education, Research)	100	https://doi.org/10.5281/zenodo.1248497
Participation to a conference	Ben Moat (NOC), Relationship between changes in the AMOC, North Atlantic heat content and SST, AGU Ocean Sciences Meeting	Portland (US), 11-16 February 2018	Scientific Community (higher education, Research)	500	https://doi.org/10.5281/zenodo.1248474

Participation to a workshop	Bogi Hansen (HAV), Presentation "Overflow through the Western Valley of the Iceland-Faroe Ridge is negligible" at the ASOF ISSG meeting	Paris (FR), 25-27 April 2018	Scientific Community (higher education, Research)	50	https://doi.org/10.5281/zenodo.1313474
Participation to a conference	Christophe Herbaut (CNRS). Evolution de l'Eau Atlantique dans l'Océan Arctique et son influence sur la glace (Poster). Colloque Bilan et Prospective du programme LIFE	Clermont-Ferrand (FR), 28-30 March 2018	Scientific Community (higher education, Research)	100	https://zenodo.org/record/1289088#.XOOm45w69D8
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) "Scotland's Marine Monitoring Actions and Their Contribution to International Efforts for a Sustained Arctic Observing System". 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), but Blue-Action was highlighted in each of these responses engaging policymakers - although on a UK level	2018	Policymakers		http://www.arcticobservingsummit.org/sites/arcticobservingsummit.org/files/ID_016_2018_Berx_AOS_ShortStatement.pdf
Participation to a workshop	Karin M. Larsen (HAV) at the EC workshop ‘’Arctic Workshop of the Transatlantic Ocean research alliance’’	Brussels (BE), 29-30 March 2017	Policy makers	30	No presentation, just participation
Participation to a conference	Marilena Oltmanns (GEOMAR): Oral presentation at the Ocean Salinity Conference; title of presentation: Variability and impacts of freshwater in the North Atlantic.	Paris (France), 6-9 Nov 2018	Scientific community	100	https://www.zenodo.org/communities/blue-actionh2020
Participation to a conference	Marilena Oltmanns (GEOMAR): Oral presentation at the 3 Cluster conference; title of presentation: Rapid cooling and increased storminess triggered by freshwater in the North Atlantic.	Berlin (Germany), 22-23 Oct 2018	Scientific community	20	https://www.zenodo.org/communities/blue-actionh2020

Participation to a workshop	Bogi Hansen (HAV): Oral presentation at Arctic Meteorological and Climate Workshop	Copenhagen (Denmark), 6-8 Nov 2018	Scientific community, policy makers	43	https://doi.org/10.5281/zenodo.2454096
Participation to a workshop	Karin Margretha H. Larsen (HAV): Oral presentation at Arctic Subartic Ocean Fluxes workshop	Bergen (Norway), 22-23 Oct 2018	Scientific community	25	https://doi.org/10.5281/zenodo.2454571
Participation to an ICES WG meeting	Bogi Hansen (HAV): Oral presentation, title: Atlantic water flow and heat transport between Iceland and Scotland.	Tórshavn (Faroe Islands), 4-6 Apr 2017	Scientific Community (higher education, Research)	20	https://doi.org/10.5281/zenodo.2671766
Participation to a workshop	Bogi Hansen (HAV), Presentation "Combining satellite altimetry and in situ observations to monitor transports of volume, heat, and salt in the Faroe Current" at the ASOF ISSG meeting	Copenhagen (Denmark), 24-26 Apr 2019	Scientific Community (higher education, Research)	50	https://doi.org/10.5281/zenodo.2669417
Participation to a conference	Ben Moat (NOC), New insights into decadal North Atlantic SST and OHC variability from a coupled climate model, at EGU 2019	Vienna (At), 7-12 April 2019	Scientific Community (higher education, Research)	100	https://zenodo.org/record/3475949
Participation to a conference	Ben Moat (NOC), New insights into decadal North Atlantic SST and OHC variability from a coupled climate model, at IUGG	Montreal (CAN), 8-18 July 2019	Scientific Community (higher education, Research)	100	https://zenodo.org/record/3475968
Participation to an event other than a conference or workshop	Stuart Cunningham (SAMS), Bee Berx (MSS). "Blue-Action: Ocean predictions and observations in response to the climate emergency". Blue-Action societal engagement meeting.	Edinburgh (UK), 16 October 2019	Scientific Community (higher education, Research), Industry, Civil Society, General Public, Policy makers, Medias	30	https://www.zenodo.org/communities/blue-actionh2020
Organisation of a workshop	Gerard McCarthy (NUIM), Stuart Cunningham (SAMS) organised a Workshop on Subpolar North Atlantic Eastern Boundary, jointly with H2020 Atlas project.	Edinburgh (UK), 14 October 2019	Scientific Community (higher education, Research)	30	https://www.zenodo.org/communities/blue-actionh2020

Peer reviewed articles

Title	**Authors**	**Publication**	**DOI**	**Is Blue-Action correctly acknowledged?**	**Open Access granted**
Subpolar North Atlantic overturning and gyre-scale circulation in the summers of 2014 and 2016	Holliday, N.P., Bacon, S., Cunningham, S.A., Gary, S.F., Karstensen, J., King, B.A., McDonagh, E.L.	Journal of Geophysical Research: Oceans	https://doi.org/10.1029/2018JC013841	Yes	Yes
On the recent ambiguity of the North Atlantic subpolar gyre index	Hátún, H., and Chafik, L.	Journal of Geophysical Research: Oceans, 123	https://doi.org/10.1029/2018JC014101	Yes	Yes
Structure and Transport of the North Atlantic Current in the Eastern Subpolar Gyre from Sustained Glider Observations	L. Houpert M. E. Inall E. Dumont S. Gary C. Johnson M. Porter W. E. Johns S. A. Cunningham	Journal of Geophysical Research: Oceans, 123	https://doi.org/10.1029/2018JC014162	Yes	Yes
The subpolar gyre regulates silicate concentrations in the North Atlantic	H. Hátún, K. Azetsu-Scott, R. Somavilla, F. Rey, C. Johnson, M. Mathis, U. Mikolajewicz, P. Coupel, J.-É. Tremblay, S. Hartman, S. V. Pacariz, I. Salter & J. Ólafsson	Scientific Reports, 7: 14576	https://doi.org/10.1038/s41598-017-14837-4	Yes	Yes
Extreme Variability in Irminger Sea Winter Heat Loss Revealed by Ocean Observatories Initiative Mooring and the ERA5 Reanalysis	S. A. Josey, M. F. de Jong, M. Oltmanns, G. W. K. Moore, R. A Weller	Geophysical Research Letters	https://doi.org/10.1029/2018GL080956	Yes	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,	Ocean Science, 15	https://doi.org/10.5194/os-15-379-2019	Yes	Yes

	K. M. H., Jónsson, S., Johnson, C., Jochumsen, K., Hansen, B., Curry, B., Cunningham, S., and Berx, B				
Atlantic water flow through the Faroese Channels	Hansen, B., Poulsen, T., Larsen, K.M.H., Hátún, H., Østerhus, S., Darelius, E., Berx, B., Quadfasel, D., Jochumsen, K.	Ocean Science	https://doi.org/10.5194/os-13-873-2017	Yes	Yes
A sea change in our view of overturning in the subpolar North Atlantic	Lozier, M. S.; Li, F.; Bacon, S.; Bahr, F.; Bower, A. S.; Cunningham, S. A.; de Jong, M. F.; de Steur, L.; deYoung, B.; Fischer, J.; Gary, S. F.; Greenan, B. J. W.; Holliday, N. P.; Houk, A.; Houpert, L.; Inall, M. E.; Johns, W. E.; Johnson, H. L.; Johnson, C.; Karstensen, J.; Koman, G.; Le Bras, I. A.; Lin, X.; Mackay, N.; Marshall, D. P.; Mercier, H.; Oltmanns, M.; Pickart, R. S.; Ramsey, A. L.; Rayner, D.; Straneo, F.; Thierry, V.; Torres, D. J.; Williams, R. G.; Wilson, C.; Yang, J.; Yashayaev, I.; Zhao, J.	Science	https://doi.org/10.1126/science.aau6592	Yes	Yes
Atlantic Meridional Overturning Circulation: Observed Transport and Variability	Frajka-Williams, E., Ansorge, I. J., Baehr, J., Bryden, H. L., Chidichimo, M. P., Cunningham, S. A., Danabasoglu, G., Dong, S., Donohue, K. A., Elipot, S., Heimbach, P., Holliday, N. P., Hummels, R., Jackson, L. C., Karstensen, J., Lankhorst, M., Le	Frontiers in Marine Science	https://doi.org/10.3389/fmars.2019.00260	Yes	Yes

	Bras, I. A., Lozier, M. S., McDonagh, E. L., Meinen, C. S., Mercier, H., Moat, B. I., Perez, R. C., Piecuch, C. G., Rhein, M., Srokosz, M. A., Trenberth, K. E., Bacon, S., Forget, G., Goni, G., Kieke, D., Koelling, J., Lamont, T., McCarthy, G. D., Mertens, C., Send, U., Smeed, D. A., Speich, S., van den Berg, M., Volkov, D., Wilson, C.				
Structure and forcing of observed exchanges across the Greenland-Scotland Ridge	Bringedal, C., Eldevik, T., Skagseth, Ø., Spall, M.A., and Østerhus, S.	Journal of Climate, 31	https://doi.org/10.1175/JCLI-D-17-0889.1	Yes	Yes
Deep Convection in the Irminger Sea Observed with a Dense Mooring Array	de Jong, M. F., M. Oltmanns, J. Karstensen, and L. de Steur	Oceanography, 31	https://doi.org/10.5670/oceanog.2018.109	Yes	Yes
Insights into decadal North Atlantic sea surface temperature and ocean heat content variability from an eddy-permitting coupled climate model	Moat, B.I., B. Sinha, S. A. Josey, J. Robson, P. Ortega, F. Sévellec, N. P. Holliday, G. McCarthy, A. L. New and J. Hirschi	Journal of Climate	https://doi.org/10.1175/JCLI-D-18-0709.1	Yes	Yes

Other publications

These are the publications currently in preparation and in review:

- de Jong, M. Femke, et al. In preparation. *Transport and variability of the Irminger Current: 2014-2016.*
- Herbaut, C., Houssais, M-N., et al. In preparation. *Mechanisms of the mid 2000s cooling in the subpolar gyre.*
- Penny Holliday, N., Manfred Bersch, Barbara Berx, Leon Chafik, Stuart Cunningham, Hjálmar Hátún, William Johns, Simon A. Josey, Karin Margretha H. Larsen, Sandrine Mulet, Marilena Oltmanns, Gilles Reverdin, Tom Rossby, Virginie Thierry, and Hedinn Valdimarsson. In review. *Ocean Circulation Changes Cause the Largest Freshening Event for 120 Years in Subpolar North Atlantic*.

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.

This is how we are going to ensure the uptake of the deliverables by the targeted audiences:

- Through dissemination at relevant scientific events (EGU…).
- Through dissemination to relevant non scientific audiences, such as civil society, businesses and policy makers: see D8.8 Societal Engagement Knowledge Exchange Nr. 2, on Ocean observations and predictions in response to the climate emergency.