Blue-Action, A4 Project and ATLAS

Joint Workshop on Subpolar North Atlantic Eastern Boundary

Fig.1. Workshop attendees. Credits: Chiara Bearzotti /DMI)

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About this document

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Summary for publication

The eastern subpolar North Atlantic (Fig. 2) has shown some striking changes in recent years, with the freshest salinities for 120 years (Fig. 3, Holliday et al., 2020) and coldest ever temperatures (Josey et al. 2018). Whether these changes are part of a cycle of Atlantic oscillations or the first indications of a long-term change in the supply of heat and salt to the subpolar gyre, through the Atlantic Meridional Overturning Circulation (AMOC), is hotly debated.

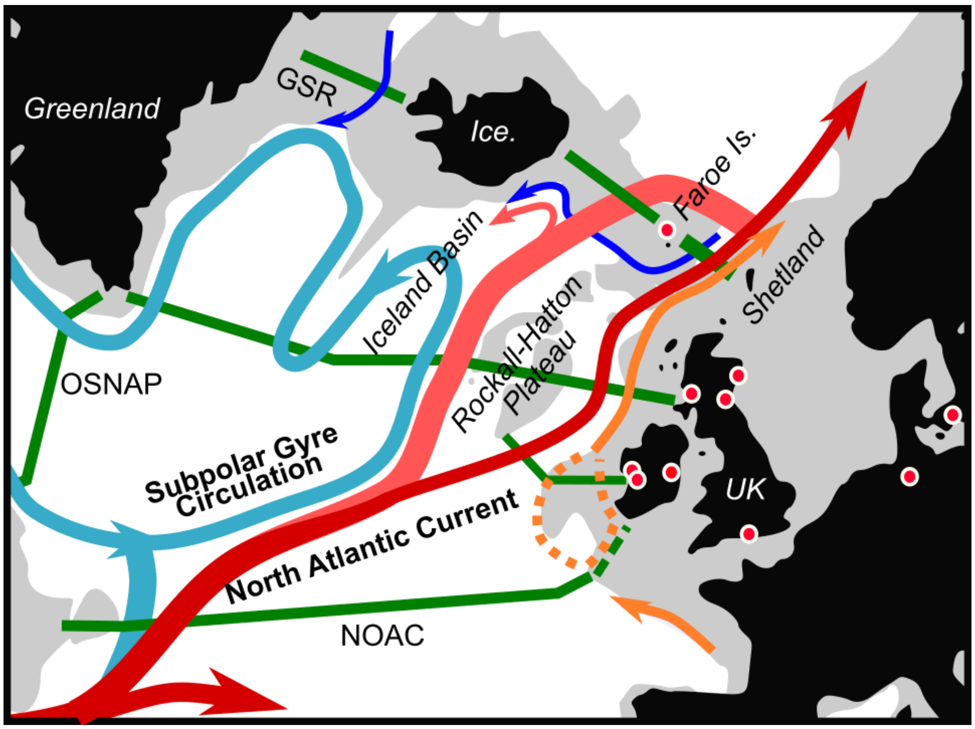

Figure 2: Major circulation patterns of warm (red) and cold (blue) water in the eastern subpolar North Atlantic. Major observing systems are highlighted in green, with planned observations in light green. A nominal depiction of the European Slope Current is indicated with an orange line (dashed for uncertain path). Red circles indicate the location of participants (Stockholm not included). Source: Gerard McCarthy.

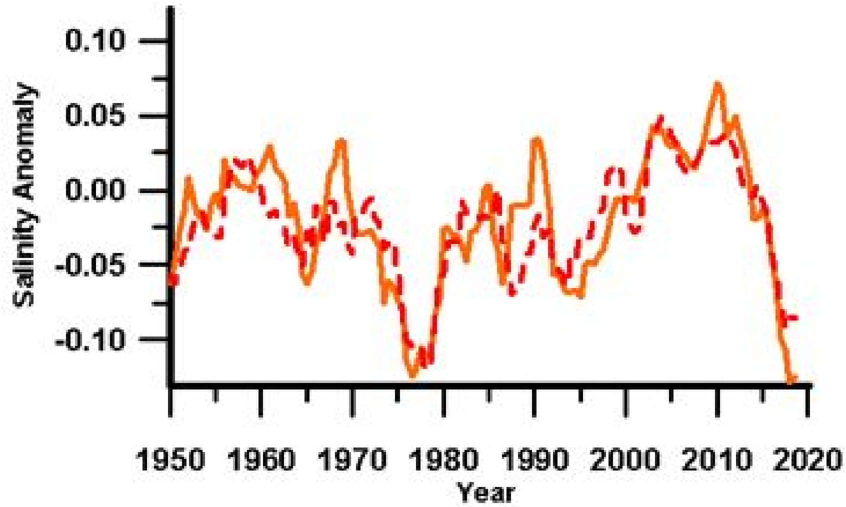

Figure 3: The freshest ever values were recorded in modified North Atlantic Water (orange), the recirculation of the north Faroe current in the Faroe-Shetland Channel were observed in recent years. North Atlantic Water (red, dashed) arriving directly to the Faroe-Shetland Channel via the Slope Current has also been freshening greatly. Source: Berit Rabe.

A vigorous AMOC and Atlantic circulation is key to the maintenance of the climate of western Europe (Årthun et al. 2017). However, the strength of the AMOC is 'very likely' to decline over the coming century due to anthropogenic climate change (Stocker et al. 2013) and a stormier, cooler future could well be in store for northwestern Europe in this scenario (Jackson et al. 2015; Woollings et al. 2012).

The emergent 'warming hole' in the subpolar North Atlantic (Drijfhout et al. 2012) has been interpreted as an indicator of a long term slowdown in the AMOC (Caesar et al. 2018; Rahmstorf et al. 2015). Direct observations are also supporting a decline in the AMOC (Smeed et al. 2018) and the 2019 Special Report on the Oceans and Crysosphere was the first IPCC report to acknowledge consensus that an AMOC decline is ongoing. It remains to be seen whether the extreme cold and fresh anomalies in the eastern subpolar gyre are a "canary in a coalmine" for a declining AMOC.

Fortunately, the eastern subpolar gyre is a region where ocean circulation is better observed now than ever before (Fig. 2), with the Greenland-Scotland Ridge (GSR), OSNAP, and NOAC mooring arrays, the latter soon to be extended onto the Irish shelf as part of the EirOOS project. This workshop was therefore timely to frame the questions of importance and highlight future directions for research in this region.

Work carried out

The workshop was held on 14 October 2019 in Edinburgh (UK), at the Hudson Beare Building, King's Buildings, Edinburgh University. The workshop was organised by Gerard McCarthy (NUIM) and Stuart Cunnigham (SAMS), with the support of the project management of Blue-Action (DMI) and Atlas (University of Edinburgh). The workshop is a collaboration of three EU-funded projects, Blue-Action and ATLAS, funded by the European Union's Horizon 2020 research and innovation programme under grant agreements No 727852 (Blue-Action) and No 678760 (ATLAS) and the A4 project (Aigéin, Aeráid, Agus athrú Atlantaigh—Oceans, Climate, and Atlantic Change), funded by the Irish Marine Institute and the European Regional Development fund (grant: PBA/CC/18/01).

This workshop brought together groups from 9 European institutions and 6 European countries to promote closer collaboration between the groups making moored and other observations along the eastern boundary of the subpolar North Atlantic. This workshop was timely and fruitful as a clustering activity between European funded Blue-Action, Atlas and the recently funded A4 project in Ireland, with extended funding for NOAC and OSNAP recently secured, and new announcements of opportunity associated with OSNAP in the UK.

We successfully described the observations that are ongoing on the eastern margin of the subpolar North Atlantic. Figures 4, 5, and 6 show the underlying velocity structure and location of the moored observations. Problems, sustainability, and opportunities were all discussed.

Scientific problems that straddle the region were discussed. In particular, focus on the European Slope Current highlighted open scientific questions that can be addressed with co-ordinated analysis of the existing arrays and co-ordinated observations in the future.

Goals of the workshop

The two aims of the workshop are:

- Descriptions of in-situ observing systems, for coordination of observing and analysis.
- Framing the scientific questions of the region.

Talks and Breakout Sessions

Welcome (Gerard McCarthy, NUIM)

Introduction to the observing arrays
NOAC, Martin Moritz (BSH)
OSNAP-East, Stuart Cunningham (SAMS)
Greenland-Scotland Ridge, Berit Rabe (MSS)

Breakout Session 1: The Big Questions
Group 1A: Bob Marsh, Clare Johnson, Tomasz Dabrowski, Marie Porter, Martin White
Group 1B: Matt Clark, Alan Fox, Levke Caesar, Stuart Cunningham, Berit Rabe
Group 1C: Ben Moat, Caroline Cusack, André Düsterhus, Sam Jones
Group 1D: Gerard McCarthy, Martin Moritz, Neil Fraser, Sam Diabaté, Kerstin Burmeister

Observing the Slope Current
The European Slope Current, Martin White (NUIG)
Observing and Understanding the Slope Current, Marie Porter and Neil Fraser (SAMS)

Modelling in the Eastern Subpolar Gyre
Modelling the Slope Current, Bob Marsh (Univ. Southampton)
Nested models on the shelf, Tomasz Dubrowski (Irish Marine Institute)

Breakout Session 2: Specific Problems
Group 2A: Martin White, Sam Diabaté, Berit Rabe, Stuart Cunningham, Neil Fraser
Group 2B: Caroline Cusack, Gerard McCarthy, Levke Caesar, Marie Porter
Group 2C: Bob Marsh, Alan Fox, André Düsterhus, Kristan Burmeister, Sam Jones
Group 2D: Clare Johnson, Matt Clark, Ben Moat, Martin Moritz, Tomasz Dabrowski

Introduction to the Observing Arrays

Presentations were heard from representatives of the NOAC, OSNAP, and GSR (Greenland-Scotland Ridge) observatories, each focused specifically on the eastern part of these arrays (Fig. 2).

NOAC
Martin Moritz, Federal Maritime and Hydrographic Agency of Germany (BSH)

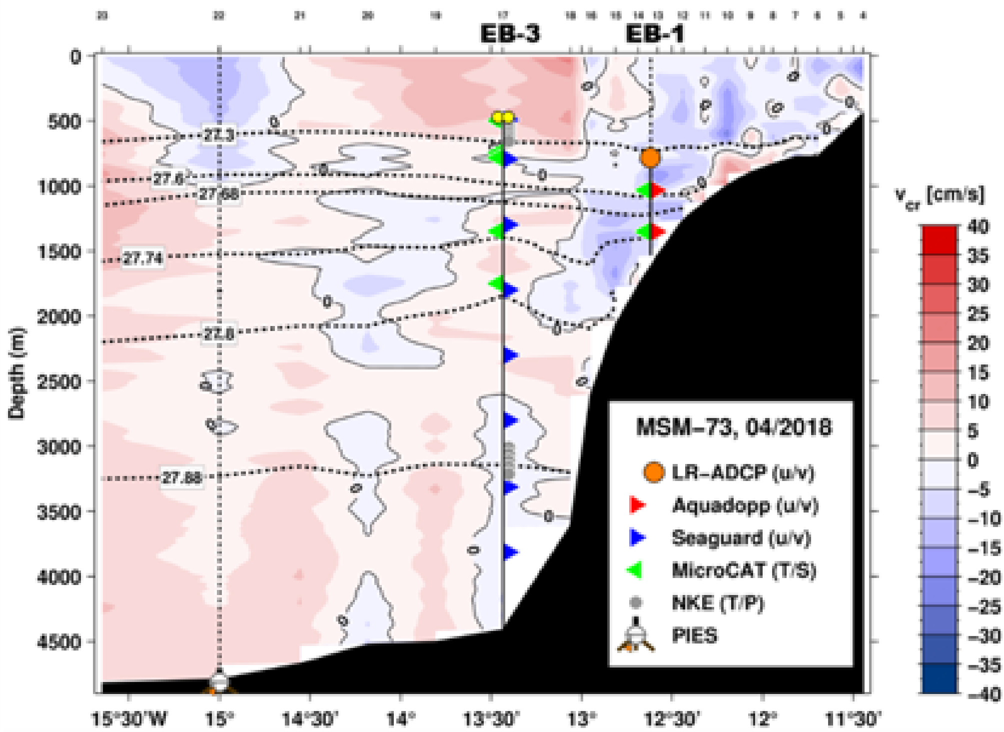

Figure 4: Location of instruments on the eastern boundary of the NOAC array at 47ºN superimposed on background LADCP velocities. Source: Dagmar Kieke

The NOAC array is a transbasin array near 47ºN led by the University of Bremen in collaboration with the BSH (Fig. 2). Originally focused on the western boundary, it has in recent years been extended with two moorings at the eastern boundary near Goban Spur, southwest of Ireland (Fig. 4). The western array is planned to end in 2020 while the eastern array will be maintained to 2021. Irish ([1]) moored observations will be added inshore of the easternmost moorings in 2020. The NOAC project has generated a large number of publications (please refer to the presentation).

[1] National University of Ireland Maynooth, Irish Marine Institute, National University of Ireland, Galway.

OSNAP-East
Stuart Cunningham, Scottish Association for Marine Science (SAMS)

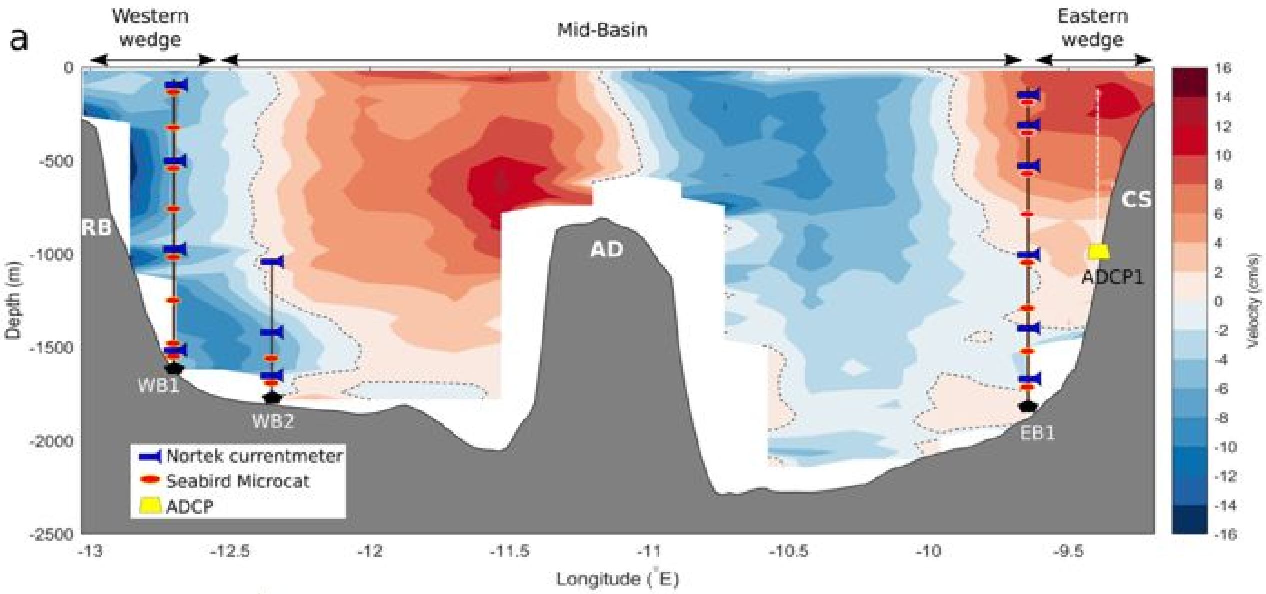

Figure 5: Locations of moorings in Rockall Trough (UK) superimposed on background LADCP measurements from the Ellett line section. RB = Rockall Bank, AD = Anton Dohn Seamount, CS = Continental Shelf. Source: Stuart Cunningham

OSNAP began in 2014 and is funded until 2024, with the eastern boundary of the array in the Iceland basin and Rockall trough capturing the warm, saline upper limb of the AMOC (Fig. 5). UK moorings in the eastern array are focused on either side of the Rockall-Hatton Plateau and on the continental shelf. Shallow regions above the Rockall-Hatton Plateau are captured by glider occupations (Houpert et al. 2018).

A number of challenges have been faced by the observations. Trawl-proof lander frame mounted ADCP measurements designed to observe the Slope Current have suffered high rates of loss. A recent investigation of the lost moorings using an ROV produced footage of the damaged lander frame buried in sediment. Fishing activity in this productive region is the suspected cause. Only 9 months of data have been recovered so far and deployments of this lander have been suspended. Glider missions have been successful in capturing narrow flows of the Slope Current and narrow jets around the Rockall-Hatton plateau. These glider-derived results highlight deficiencies in the resolution of gridded altimeter products, traditional hydrographic sections, and Argo float profiles.

Faroe-Shetland Channel
Berit Rabe, Marine Scotland Science

The transport and properties in the Faroe-Shetland Channel (FSC) are observed by a collaboration of Marine Scotland Science and the Faroe Marine Research Institute. Direct observations of the transport in the channel date back to 1993, with hydrographic properties observed by regular ship hydrography since the 1950s (Fig. 3). The observing systems have recently been assessed for optimisation in both the FSC (Fig. 6) and the Faroe Current north of the Faroe Islands. Future monitoring will integrate satellite altimetry with optimised mooring configurations (D2.8, due June 2020). Transport in the FSC has been stable although properties have been observed to vary widely. The warmest, most saline values were recorded around 2010, with the freshest values ever recorded in recent years.

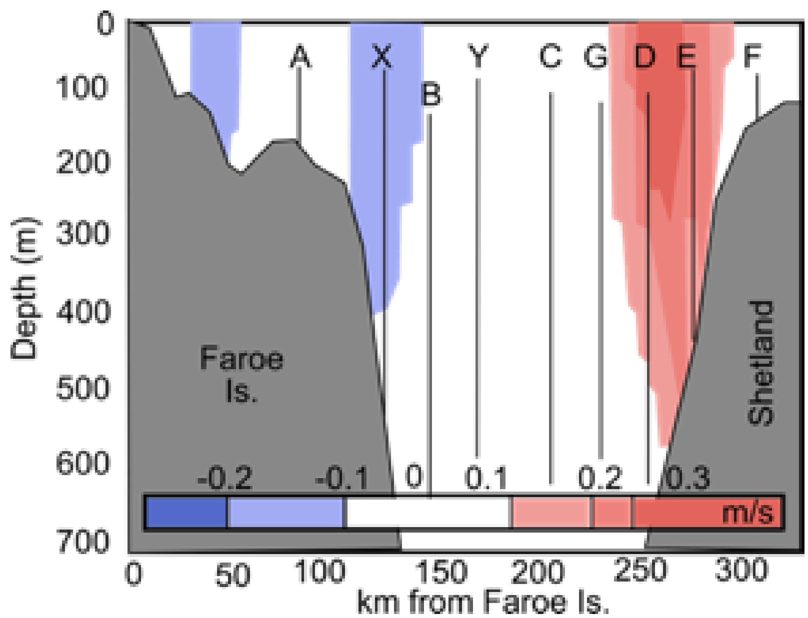

Figure 6: Velocity across the Faroe-Shetland Channel after (Rossby et al. 2018) and positions of full mooring array (letters and vertical lines) across the channel after (Berx et al. 2013).

Inflow to the North Sea is also investigated by MSS, with radar observations in the Fair Isle Gap between the Shetland and Orkney islands (Sheehan, PhD thesis, University of East Anglia, 2019), and model and glider investigations east of the Shetland Islands (Hughes, PhD thesis, University of Aberdeen, 2014)

Observing the European Slope Current

Observations at the eastern boundary of the subpolar North Atlantic stretch from below 50ºN to north of 60ºN. This offers an unprecedented opportunity to observe the oceanographic phenomena that link these latitudes. In particular, the European Slope Current (Fig. 2), which has its origins off Iberia and can be traced northwards through the Faroe-Shetland Channel. Observing the Slope Current is difficult due to its small cross-sectional area. Consequently, fundamental questions remain about its continuity and relationship to broader Atlantic circulation.

The European Slope Current
Martin White, National University of Ireland Galway (NUIG)

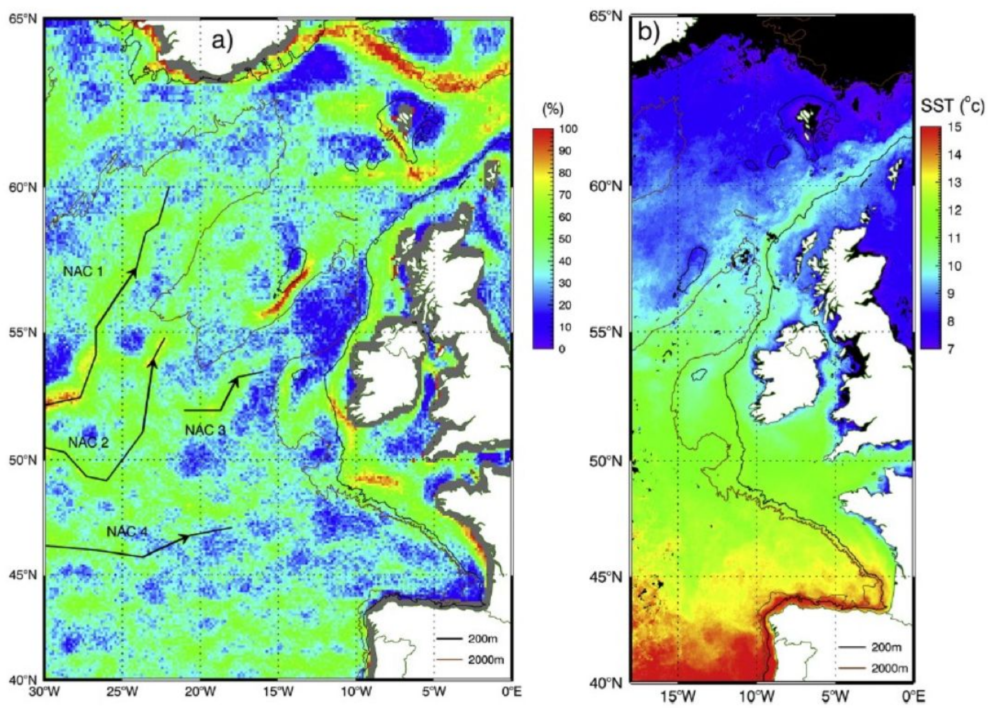

Figure 7: (a) Winter front climatology. (b) Sea surface temperature in January 1996. The Slope Current is evident north of 57ºN as a highway of warm water into the Nordic Seas. From (Xu et al. 2015).

The Slope current is strongest and most continuous in winter, where northward velocities can be traced in altimeter data from Iberia to the Shetland Islands (Xu et al. 2015). Most of the water flowing through the FSC has its origins in the Slope Current and in winter the Slope Current is an evident pathway for warm Atlantic water into the Nordic Seas (Fig. 7).

The Slope Current can act as a barrier but also a conduit between the open ocean and shelf Seas. The sharp wintertime front associated with the Slope Current separates colder shelf waters from the warmer waters of the Rockall Trough, west of Ireland (Fig. 7). The same current can act as a conduit for warm Atlantic water into the North Sea (Marsh et al. 2017).

A particular question relates to the continuity of the current around the Porcupine Seabight, southwest of Ireland. Near Goban Spur, the current is known to reverse seasonally (Pingree et al., 1999). Whether the Slope current flows around the outside of the seabight directly west of Goban Spur to the west flank of the Porcupine Bank or inshore of the Porcupine Seabight (Pingree et al. 1999) is an unresolved question.

The generating force for the current is wind stress and the meridional gradient of density (poleward decrease in dynamic height) between Biscay and the Rockall trough. As such, the North Atlantic Oscillation (NAO), as the leading atmospheric mode of variability, has a strong influence on the Slope Current. North of the FSC, the Norwegian Slope Current was found to be strongly correlated with the local wind stress curl (Orvik and Skagseth, 2003). South along the Bay of Biscay and Iberian margins, lower NAO is correlated with higher SSTs indicative of a stronger Slope Current. The zero line of NAO-related sea level pressure anomaly is close to the Porcupine Bank and could mark a divisor between differing regimes of Slope Current behaviour. What conditions control the linkage south of Porcupine Seabight and slope current regime to the north of the Porcupine Bank is an outstanding question.

Observing and Understanding the Slope Current

Marie Porter and Neil Fraser, Scottish Association for Marine Science (SAMS)

Observing the Slope current is challenging due to its small cross-sectional structure and filamental nature. Traditional ship hydrography is too coarsely spaced to routinely capture it. Gridded altimetry is also not sufficient resolution to capture these filamental jets (Houpert et al. 2018). New tools are now available to observe this type of structure. Gliders offer an excellent tool for studying these flows as glider profile spacing is much shorter than typical shipboard hydrography and gliders can survey in winter when weather frequently prohibits ship survey (McCarthy et al., 2020).

Repeated glider surveys of the Slope current have been undertaken by SAMS over the past decade across the Malin shelf. Data are gridded and detided. The resulting cross sections reveal the changing patterns of the Slope Current in winter and summer (Porter et al., *in prep.*).

Modelling in the E. Subpolar Gyre

Modelling the Slope Current
Bob Marsh, University Southampton, invited guest

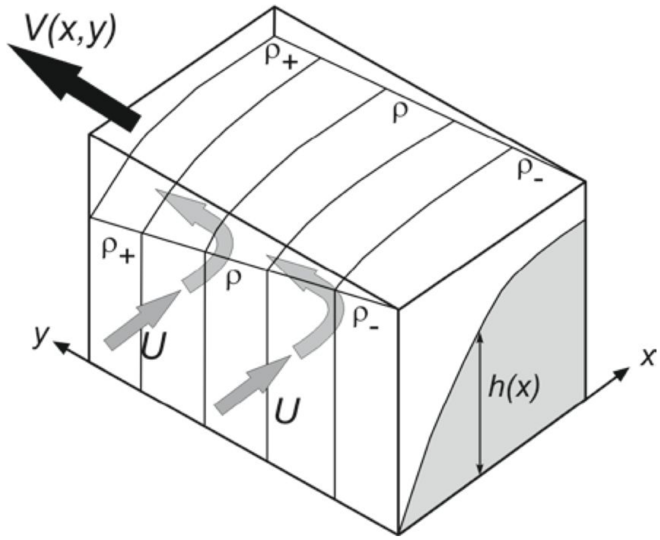

Figure 8: Dynamics of the Slope Current. Along-shelf is approximately meridional (y-direction) and cross-shelf is approximately zonal (x-direction). Zonal density (ρ) gradients increase to the north, leading to a strengthening of the meridional flow (V) in the Slope Current. The current is fed by zonal currents (U) from the west through branches of the North Atlantic Current. From (Simpson and Sharples 2012), their figure 10.5.

Cross-shelf density gradients set up a difference in sea surface height across the continental shelf and are linked with the (along-) Slope Current strength. These gradients increase with latitude, therefore the strength of the Slope Current increases with latitude. Meridional gradients in density support zonal geostrophic currents. In the subpolar North Atlantic, offshore of the continental shelf, a north south density gradient supports, the North Atlantic Current, which in turn feeds into the Slope Current.

Meridional density gradients in the subpolar North Atlantic underwent a major weakening in 1996-98, that was linked to extensive warming of the subpolar gyre (Häkkinen and Rhines 2004). This reduction in meridional gradient of density weakened the geostrophic inflow and consequently weakened the Slope Current.

This variation of the Slope Current can be understood with a modified formulation of Huthnance (1984). Using glider data to improve parameterisation, the seasonality of the Slope Current can be identified (Fraser et al., *in prep.*).

Changes in the Slope Current have important impacts on the adjacent shelf seas. The Slope Current is a highway for subtropical species into the northern North Sea. Subtropicalisation is expected to occur due to climate change, with the paradigm generally of northward invasion of subtropical species as cooler regions warm. However, the gateway to the North Sea is from the north, through the Fair Isle gap, rather than the south. Therefore subtropicalisation is evident progressing southwards from the Fair Isle gap (Montero-Serra et al. 2015) and emphasizes the importance of the Slope Current on changing regional ecosystems.

Nested models on the shelf
Tomasz Dubrowski, Irish Marine Institute (MI)

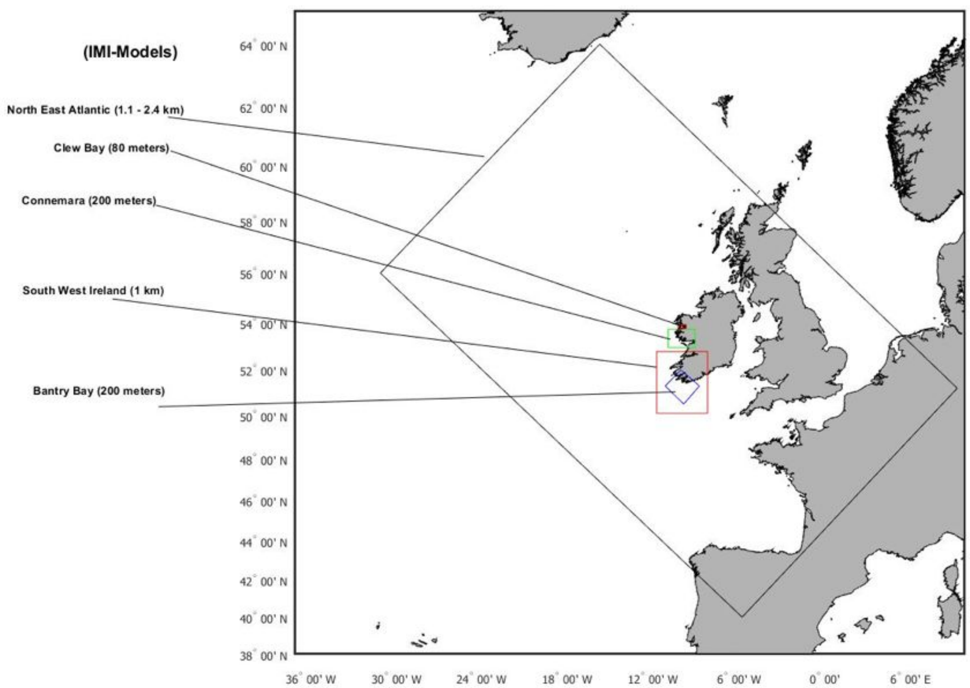

Figure 9: Domains of Marine Institute nested models. Source: Thomas Dabrowski.

Difficulties occur in modelling the Slope Current and on-shelf processes, including those relevant to aquaculture and fisheries, due in particular to the small spatial scale of the current. A solution to this problem is the use of nested models. A number of such models exist including the UK Met Office's Atlantic Margin Model model. The Irish Marine Intstitute has a number of nested models based on ROMS 3.7, with SWAN for waves, and forced with a global Copernicus model. The models are validated against observations with tidal, storm surge, and temperature and salinity characteristics all well simulated (Dabrowski et al. 2015).

Main results achieved

In addition to the closer collaboration and coordination fostered by this workshop, results focused on the formulation of questions for future collaboration through two breakout sessions. Each group distilled their discussions to a list of questions and ideas. *This was a 'questions' rather than an 'answers' workshop.*

Breakout Session 1: The Big Questions

Following a 25 minute breakout session, the following list of ‘Big Questions’ was produced.

- Are water mass changes (i.e. Θ-S) properties changing in conjunction with the fresh anomaly?
- Is warm and fresh becoming a new state of the subpolar gyre?
- How will salinity anomalies propagate and mix?
- Are these changes a new normal, a short-term anomaly, or part of a cycle?
- What are the ecosystem impacts of the recent changes?

- What are the relative roles for advection (path changes) and air-sea interaction in recent changes?
- What has changed: AMOC, SPG index, wind stress curl, upper ocean density?
- How does the fresh anomaly interact with ocean boundaries (dynamic response)?
- Where does the freshwater come from (Greenland melt?) and where will it go?
- How can subtropical and subpolar influences be separated?
- What are the relative contributions of horizontal (gyre) and overturning circulation for the import of heat and salt/freshwater to the eastern basins?
- Why do models disagree on the predicted changes in eastern pathways, and does this limit the confidence in the predictability of the Nordic Seas?
- Is predicting the atmosphere critical for subpolar North Atlantic ocean circulation? And is there a source of predictability (e.g. higher latitudes)?

Contributors
Group 1A: Bob Marsh, Clare Johnson, Tomasz Dabrowski, Marie Porter, Martin White
Group 1B: Matt Clark, Alan Fox, Levke Caesar, Stuart Cunningham, Berit Rabe
Group 1C: Ben Moat, Caroline Cusack, André Düsterhus, Sam Jones
Group 1D: Gerard McCarthy, Martin Moritz, Neil Fraser, Sam Diabaté, Kerstin Burmeister
Group 1E (remote): Penny Holliday, Loic Houpert, Leon Chafik

Breakout Session 2: Specific Problems

Following the talks focused on the Slope Current, a second breakout session focused on specific questions that we could address as a group.

- What is the north-south coherence of the Slope Current?
- What is the importance of the overflows and interactions of overflows with the Slope Current?
- How can the Great Salinity Anomaly of the 1970s be used to interpret the ongoing changes in the subpolar North Atlantic?
- How can we combine all observations from Goban Spur to the FSC and can this feed into better predictions?
- How do large scale (Atlantic) and small scale (shelf edge) observations fit together?
- How can mooring and glider data be combined?
- What determines the timescales and drivers of the Slope Current?
- What is the interplay between long term slow variability and synoptic events? And how does this relate to associated changes in ecosystems?
- Can we move towards a statistical description of the processes (probability, risk)?
- Can we anticipate boundary changes given that we have good simulations/reanalyses of open ocean processes?
- Can we integrate gliders/hydrography into the eastern NOAC observations?
- Can we trace variability all the way to the North Sea?
- At OSNAP, can oxygen measurements be extended to the mid-Atlantic Ridge?
- Can we have more high resolution (nested) models on the shelf to reduce uncertainty?

A number of strategic questions were also raised.

- How are modelling and observations combined in a coherent manner?
- How can observations be sustained?

Contributors:
Group 2A: Martin White, Sam Diabaté, Berit Rabe, Stuart Cunningham, Neil Fraser
Group 2B: Caroline Cusack, Gerard McCarthy, Levke Caesar, Marie Porter

Group 2C: Bob Marsh, Alan Fox, André Düsterhus, Kristan Burmeister, Sam Jones
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Impact

Prediction skill on timescales of multiple years depends on the ocean. This is one reason that the subpolar North Atlantic is the most predictable region on the planet on timescales up to decades: models can correctly simulate Atlantic ocean circulation leading to better predictions. As the systems develop, **refining the origin of the skill is necessary. For this improved understanding of the regional circulation is necessary.**

The second half of our workshop focused on the European Slope Current. While a small current in comparison to the North Atlantic Current and Gulf Stream, it has great importance for the transmission of materiele from the subtropics to the European shelf seas and for the delivery of heat to the Arctic: the warmest waters that cross the FSC are derived from the the Slope Current.

Key take-home messages for the policy making

We highlighted a number of important questions that need to be addressed to understand the eastern subpolar North Atlantic, including:

- How do the extreme changes observed in the Atlantic in recent years (cold and fresh anomalies) fit in the picture of a changing climate: declining Atlantic Meridional Overturning Circulation , changing atmospheric patterns. And what are the future implications of these?
- How do small (spatial) scale ocean circulation features, such as the European Slope Current, that new technology is only now enabling us to observe, connect with large circulation patterns such as the Atlantic Meridional Overturning Circulation and heat transport towards the Arctic?

An improved understanding of these questions could greatly improve the representation of heat transport across the Greenland-Scotland Ridge towards the Arctic and help us **better understand the connection from lower latitudes to high latitudes**. The opportunity is also timely at the moment due to the number of independently-funded observing arrays in the region.

There is need for the scientific community to receive **ad-hoc funding from the next research and innovation programme (Horizon Europe) to address these questions and to sustain on the long-term the observing arrays**.

There is **strong potential for improved forecasts to transfer to business stakeholders**, in particular with the fisheries and aquaculture communities. For example, subtropical species arrive in the North Sea from the north, due to being transported by the Slope Current. This surprising fact has important implications for understanding the spread of subtropical species due to climate change and their impact on fisheries and ecosystem. It underlines the importance of understanding these Slope Current dynamics.

Links built

This workshop brought together groups from 3 European funded projects (Blue-Action, Atlas, A4) across 9 European institutions and 6 European countries to promote closer collaboration.

In particular, the workshop was one of the first events to specifically bring together the groups making moored and other observations along the eastern boundary of the subpolar North Atlantic (NOAC, OSNAP, FSC).

Contribution to the top level objectives of Blue-Action

This deliverable contributes to the achievement of the following objectives and specific goals indicated in the Description of the Action, part B, Section 1.1: http://blue-action.eu/index.php?id=4019

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

Ocean circulation is the origin of the predictability in the North Atlantic. Improved understanding of the constituents of ocean circulation will improve predictions. The workshop had a strong focus on the Slope Current, which is the origin of much of the heat going to the Nordic Seas. Improved representation of these individual currents will improve prediction systems.

Objective 5 Optimizing observational systems for predictions

This workshop brought together for the first time the three transbasin moored arrays in the North Atlantic. The collaboration and cooperation engendered will lay the groundwork for optimised observing in the region. This directly feeds into the objectives of Blue-Action.

References (Bibliography)

- **The A4 project (Aigéin, Aeráid, agus athrú Atlantaigh—Oceans, Climate, and Atlantic Change**) targets three areas of physical oceanography and climate research where impactful and strategically important progress can be made. These areas are: understanding Atlantic variability and its connection to the Irish shelf (WP1); advancing knowledge of Irish Sea level change in an Atlantic context (WP2); and development of predictive capacity on decadal timescales for planning and management (WP3). All three strands are integrated to provide comprehensive, stakeholder-focused reports. The project is funded by the European Regional Development Fund in Ireland https://www.maynoothuniversity.ie/news-events/maynooth-university-oceanographer-dr-gerard-mccarthy-leads-2-million-climate-change-project-funded
- **OSNAP** is an international program designed to provide a continuous record of the full-water column, trans-basin fluxes of heat, mass and order cialis lowest price freshwater in the subpolar North Atlantic https://www.o-snap.org
- **NOAC** The Bremen NOAC observing system in the subpolar North Atlantic https://usclivar.org/sites/default/files/meetings/2014/amoc-presentations/KIEKE_2014USAMOC.pdf
- A recent Science Foundation Ireland (SFI) research infrastructure award, the **EirOOS project**, funded in 2018, provides the means to complete the transfer to new technology, placing the network on a sound basis for many years to come. This work includes leveraging additional data acquisition of key climate variables, most notably carbon dioxide exchange across the air-sea boundary. This technically challenging addition to the suite of measurements adds a tool to assist the research community in assessing ocean acidification. https://www.ouroceanwealth.ie/sites/default/files/Publications/harnessing_our_ocean_wealth_-_review_of_progress_2018-web.pdf

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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 in activities organised jointly with other H2020 projects	Blue-Action, A4 Project and ATLAS Joint Workshop on Subpolar North Atlantic Eastern Boundary	Edinburgh (UK), 14 October 2019	Scientific Community (higher education, Research)	20	https://zenodo.org/record/3698165

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: The workshop has promoted a closer collaboration between the groups making (especially moored) observations formally across three projects mentioned above, but also with contributions from (H2020) AtlantOS, (H2020) JERICO NEXT and a number of Danish-funded projects. The results of the workshop will be used for two papers in preparation, authored by the teams at the workshop.