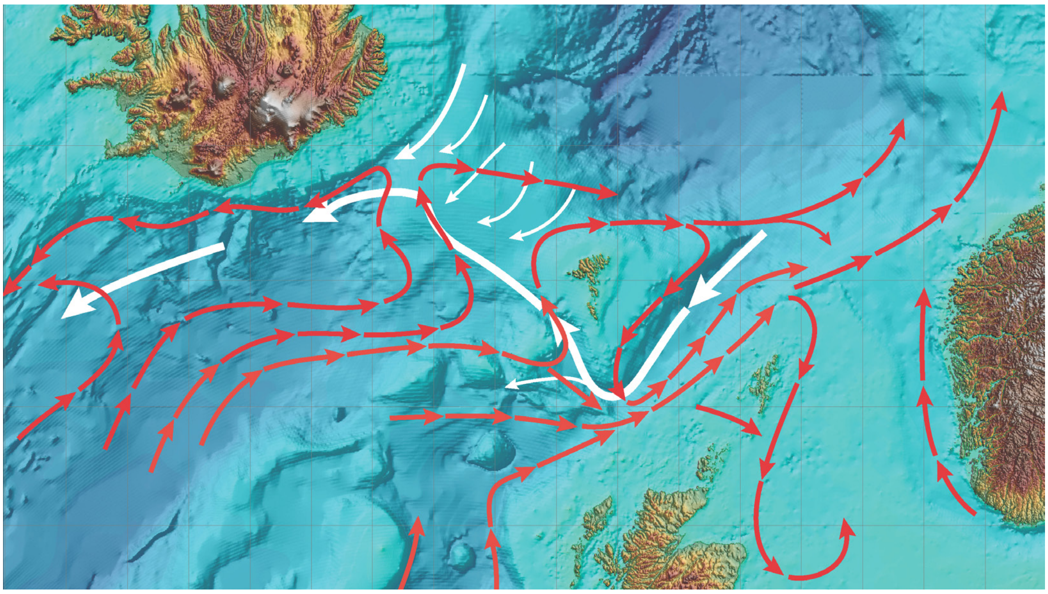
HAVSTOVAN
FAROE MARINE RESEARCH INSTITUTE

Workshop on currents and transports across the Iceland-Faroe-Scotland Ridge

Tórshavn · March 2017



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TECHNICAL REPORT

Cover:
The circulation diagram was kindly produced by Keith Mutch and Mhairi Sinclair (Marine Scotland Science)

Content

Introduction

The vertical circulation of the ocean, often referred to as the meridional overturning circulation, the thermohaline circulation, the conveyor belt, or the abyssal circulation, encompasses the significant transformation of water properties driven by cooling at the surface at high latitudes, and 'ocean-wide' upwelling through the downward diffusion of buoyancy through the main thermocline. In the North Atlantic Ocean, there are two areas where the transformation of upper ocean water to dense deep water takes place, namely the Labrador Sea and the Nordic Seas. The former produces water of intermediate density, while the latter produces water of greater density that pools at depth in the Greenland Sea and eventually spills back into the deep North Atlantic over the sills between Greenland, Iceland, the Faroe Islands and Scotland. Whereas this deep return takes place over all sills, almost 90% of the warm water entering the Nordic Seas by the upper ocean circulation does so between Iceland, the Faroes and Scotland. Thus, if one wants to observe the strength of the meridional overturning circulation (MOC), this is one of the key choke points for doing so.

Observational History

Early hydrography

The regions close to the shallow sills between Iceland, Faroe Islands and Scotland have been observed and studied for decades. These activities have been a combination of research-focused projects and government-funded monitoring programs, which have resulted in sustained ocean observation efforts.

The first measurements in the Faroe-Shetland Channel (FSC) were collected in 1893 by Dr H. N. Dickson in support of multi-disciplinary studies of the region. During the 1890s and 1900s several Nordic surveys were conducted in the area between Iceland, Scotland and Norway, e.g. led by Helland-Hansen. Since then researchers have continued to survey the Nolsoy-Flugga and Fair Isle-Munken (Figure 1) sections mainly on an annual basis, but during some periods (e.g. the 1950s) the surveys have been much more frequent (up to eight times per year). Since the Nordic-WOCE programme (1993-1997), direct current meter observations and more regular hydrographic surveys (up to six times per year) have contributed data to various research and monitoring programmes.

Measurements on the Iceland-Faroe Ridge (IFR) were also obtained on international surveys around 1890-1910, but unlike in the FSC, regular surveys were not established there. In the late 1950s, the importance of the circulation across the Greenland-Scotland ridge was manifested and this led to the international Overflow-surveys arranged by ICES (International Council for Exploration of the Sea) on the IFR in 1960 and 1973, the latter also covering the Faroese Channels. Since then, regular sections have only been maintained in the vicinity of and partly on the IFR.

Modern measurements

Starting some 20 years ago, several observational programs have been established to measure the flows towards the Nordic Seas on the one hand, and the return flow over the sills on the other. These activities have also been very effective at tracking changes in water properties over time. Since 2008, observations from the ferry Norröna, during her weekly transits from the Faroes to Denmark and Iceland, have measured currents through the IFR and the FSC. Since 2013 this vessel also takes monthly automated expendable bathythermograph (XBT) sections to map out the temperature field. Other investigators have also embraced some of the emerging novel technologies in these regions; for example by looking at the IFR overflow using ocean gliders, and by using satellite altimetry as a powerful tool to map out spatio-temporal variability of surface currents.

Figure 1 shows most of the sustained ocean observation programs in the region of interest. Repeat hydrography is collected along all these sections, except for the Norröna transects, which only has XBT data collection. Additionally, a number of hydrographic sections extending out from Iceland provide data from the western part of the IFR (not shown in Figure 1). As mentioned, direct observations of currents were established in the late 1990s along several of the sections. These observations have mainly been along the FIM, FBC and FC sections and in 2016, the WOW project started collecting moored current meter observations in the Western Valley (east of Iceland).

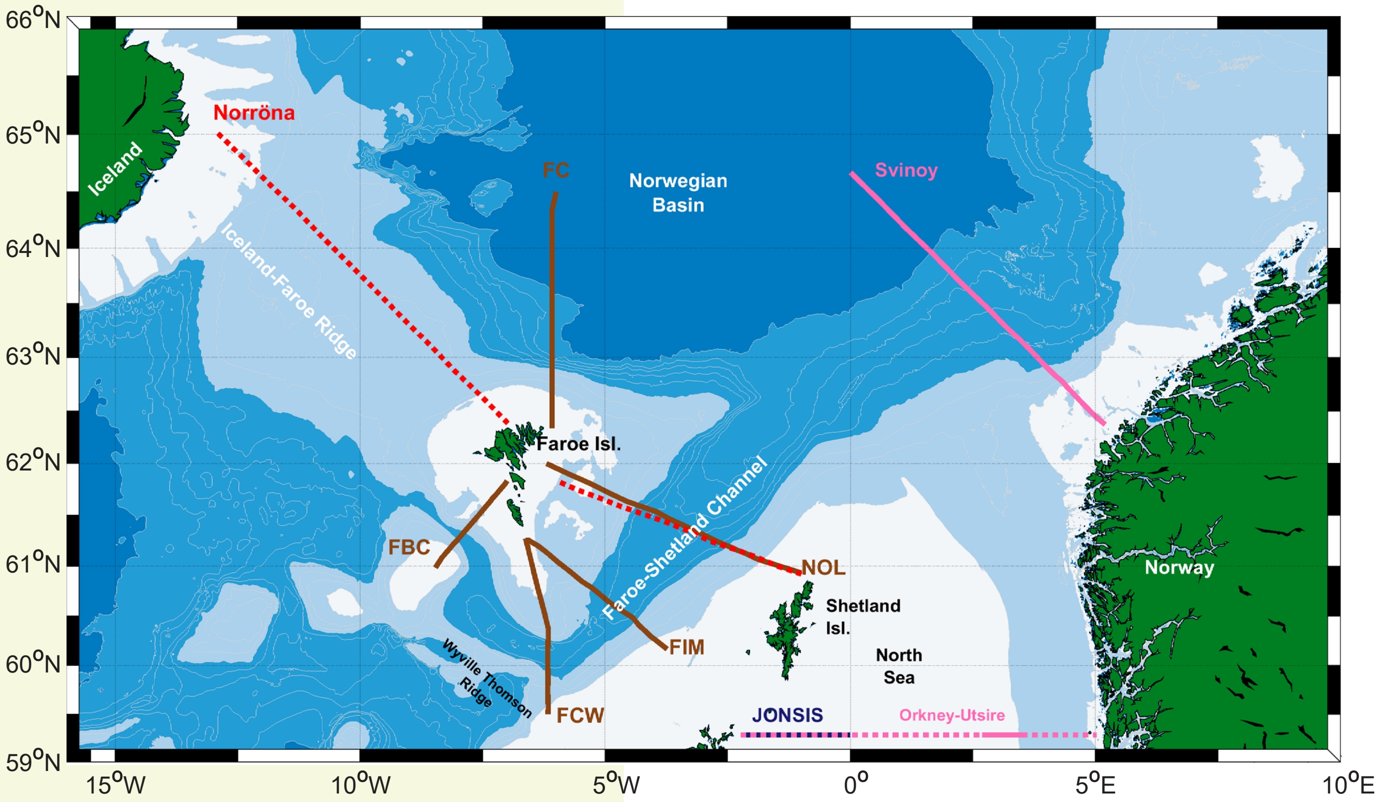


Figure 1. Map of repeat sections in the Iceland-Faroes-Scotland region. Bathymetry is coloured by 4 intervals: shallower than 200 m, between 200 m and 800 m, between 800 and 2000 m, and deeper than 2000 m. Bathymetry contours are every 200 m between 200 m and 2000 m. The following sections are shown: Nolso-Flugga (NOL, also referred to as E-section); Fair Isle-Munken (FIM, also referred to as S-section); Faroe-Cape Wrath (FCW, also referred to as Z-section); Faroe Bank Channel (FBC, also referred to as V-section); Faroe Current (FC, also referred to as N-section); Svinoy; JONSIS (Joint North Sea Information System). Additionally, typical Norröna tracks across the FSC and along the IFR are shown (dotted red lines).

The hydrography along the NOL, FIM and FCW sections is maintained by MSS, FAMRI and collaborators. The FBC and FC sections are maintained by FAMRI, the Svinoy section by Norwegian collaborators and the JONSIS section by MSS.

The workshop

In February 2016, several investigators active in these waters between Scotland and Iceland met at the Ocean Sciences Meeting in New Orleans to explore the idea of a workshop to discuss their activities in an informal setting. The idea 'took root' and a workshop was held in Torshavn January 9-10, 2017. This report summarizes the main outcomes of the meeting. A list of the workshop participants, agenda and most of the presentations, in the form of long abstracts, are included as appendices.

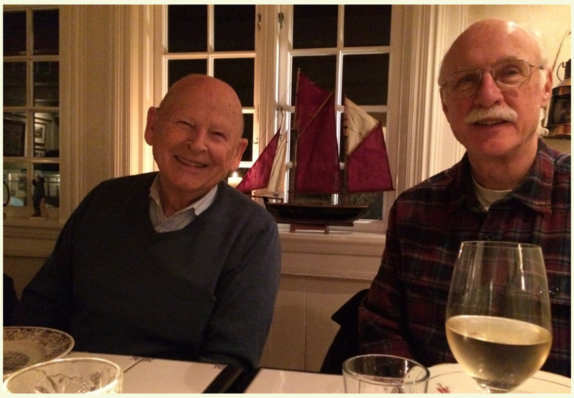
The fundamental objectives of the workshop were to meet and learn more about our various activities, and to explore ways to team up and complement our approaches towards a more complete understanding of the physics and dynamics of this central link in the global MOC. The two principal threads we had in mind were the scientific objectives, and the means by which we seek to achieve or implement these.

The first 1½ day of the two–day workshop was spent on individual reviews of our various activities, with plenty of time for discussions along the way. The purpose was to bring us all up to date on the present state of knowledge (see Appendices A4-A17 for long abstracts). After the presentations, ideas were exchanged on how we can move forward and what the obvious next steps are. Here, the circulation in the FSC was discussed and how the various data sets can be combined to get a better understanding of the circulation (For instance a working group was established to look at altimetry and XBT data in more detail to see if improved geoid estimates could be obtained). Different methods and data to calculate transport values in the FSC inflow and the Iceland-Faroe inflow were discussed. Those participants involved in fieldwork in the FSC discussed future observations.

Visit from Smyril Line

As mentioned, one of the monitoring platforms in this area is the ferry Norröna. The Norröna is run by Smyril Line and Jógvan í Dávastovu from the company was invited to participate in the workshop. He gave a short presentation where he informed the group about a new cargo vessel that Smyril Line has bought and where it will be possible to install an Acoustic Doppler Current Profile (ADCP) (similar to the one on the Norröna). Since the start of the Norröna program, Tom Rossby and Charlie Flagg have had an excellent cooperation with Smyril Line and Jógvan í Dávastovu, and they thanked Smyril Line for contributing to science through this program. Tom Rossby also mentioned that the U. S. National Science Foundation in autumn 2016 sent Smyril Line a *letter* and *certificate of appreciation* for their support of the Norröna program, without which the program would not be possible. More information on the Norröna program is found in the appendices by Tom Rossby (A4) and Charles Flagg (A10).

The Norröna program: From left Dr. Tom Rossby, Jógvan í Dávastovu (quality management, safety & security at Smyril Line) and Dr. Charles Flagg. In the background is Smyril Line's new cargo vessel (Photo by Léon Chafik)



Dr. Tom Rossby and Dr. Charles Flagg (Photo by Anne Britt Sandø).

Science summary

Scientific discussions at the meeting highlighted the complementary nature of the expertise in the room. The knowledge we bring derives from the tools we have at our disposal. These have various strengths and weaknesses, and the discussions helped guide us in how to best utilize them in a complementary way. The following section highlights some key scientific questions in the Iceland-Faroe-Scotland region, based on discussions during the workshop.

The Atlantic inflow between Iceland and the Faroes converges in the eastward flowing Faroe Current (FC) north of the Faroe Islands. This flow splits at the NE corner of the Faroe Plateau, and one branch – the Southern Faroe Current (SFC) – continues southwest along the Faroe slope in the FSC (Hátun, 2004). Observations from the Norröna project have suggested that the SFC is stronger than previously anticipated. This and the associated lower transport estimate of Atlantic water through the FSC (Rossby and Flagg, 2012), were the main motivation for the workshop. Much of the discussion thus revolved around the SFC.

Splitting of the FC

Strong atmospheric forcing – represented by a positive North Atlantic Oscillation (NAO) Index – results in a tightening of the boundary currents around the Norwegian Sea, stronger topographic steering and thus more southward flow from the FC, and into the FSC. This southward flow is also stronger during winter. The highly variable wind stress curl is likely the most important driver. The Atlantic water, which has turned south from the FC joins the Inner branch along the Norwegian slope and likely reaches the high Arctic. The large-scale pressure field (involving the overflows) can violate the otherwise strong topographic control, which results in strong eddy activity in the northern end of the FSC. Altimetry data reveal a southward propagation of cold-core eddies from the southern Norwegian Sea and into the FSC. An Empirical Orthogonal Function (EOF) analysis of the sea surface height (SSH) field shows low SSH over the southern Norwegian Sea and the FSC during NAO-high years. A comparison between the SSH principal component and ADCP observations north of the Faroes and in the FSC verify the increased clockwise circulation around the Faroe Plateau during NAO-high years. Questions focused on whether the southward transport consists of trains of eddies or a steady flow. A preliminary (unpublished) study, using three Aanderaa mooring, shows that the SFC at ~650 m depth (~61.9°N) is very rectilinear. Drifters indicate converged southward flow across the NE tip of the Faroe Plateau at about 4°W. The FARMON project will deploy two ADCPs in this cross-over region for a one-year observational period (summer 2017 to summer 2018) to study the circulation at the NE tip of the Faroe plateau.

Retroflection of the SFC

The southward propagating cyclonic cold-cored eddies might draw water from both the Faroe and Shetland slopes, and thus distort the boundary currents. This results in a retroflection of the SFC, bringing its water firstly into the FSC and eventually into the pole-ward boundary flow along the European Continental slope. The presence of a cold-core eddy can be observed as an uplifted 5°C isotherm (doming) in the central FSC, and as lower SSH. XBT data along the Norröna track show large vertical undulations of this isotherm – e.g. it was deep during 2014, but ascended much during 2015 (colder conditions). ADCP data from Norröna shows strong correlation between the flows in the SFC and in the boundary current along the Shetland slope – strong southwestward flow in the SFC coincides with increased pole-ward flow along the Shetland slope. This situation is, furthermore, associated with an uplifted 5°C isotherm and lower SSH in the central FSC. A dipole SSH index has been constructed to describe this variability. The gridded altimetry products are, however, too smooth for detailed boundary current studies in the region. As the Norröna section roughly coincides with both an altimetry track and a long-term standard hydrographic section (the Nolsoy-Flugga, Figure 1), there is an opportunity to establish closer connections between the Norröna project, altimetry studies and other available data from the FSC. To complement the planned ADCP moorings at the NE Faroe Plateau corner (see above), participants agreed to instrument three further ADCP moorings on the Norröna track (summer 2017- summer 2018). One will be deployed in the current core on the Shetland side, one in the central FSC and one in the SFC, where the Norröna track, the altimetry track and the standard hydrographic section overlap. There may also be an opportunity to supplement this study with opportunistic ocean glider observations in summer 2017 (MASSMO4).

Flow from the FSC into the FBC – or not?

The canonical circulation diagram, first presented by Helland-Hansen and Nansen (1909), shows that all of the SFC water retroflects in the FSC, and eventually flows north. A number of studies – including the one based on the Norröna data (Rossby and Flagg, 2012) – have since presented a flow scheme involving appreciable flow from the FSC into the Faroe Bank Channel (FBC). However, a recent study (Hansen et al., in prep.) using data from a wide range of oceanographic observations supports the original scheme. With many of the key authors of these studies in the room, these two opposing flow schemes were discussed at length.

The updated Norröna data show weaker southward flow in the SFC, compared to the first presentation by Rossby and Flagg (2012). A line of ADCPs, deployed along a section south from the Faroe Plateau (the NWZ-line, Figure 1), showed clear correlations between the flows on each side of the channel (comparable to the Norröna data farther north, see above). This could be interpreted as a stationary eddy, or as current jet, whose core position shifts meridionally. This current jet is associated with the northwestward rising 5°C isotherm – the boundary between the poleward flowing Atlantic water masses and the equatorward flowing subarctic water masses. The unknown undulation of this interface continues to be a source of uncertainty in deciding on the validity of the two flow schemes.

Overflows

The second day was partially devoted to discussing the two main overflow branches across the Iceland-Scotland Ridge.

a) The Faroe Bank Channel overflow

At the FBC sill, the overflow transport has been stable since the early 1990s. Since the early 2000s, however, it has become 0.1°C warmer, but this has been accompanied by increasing salinities, which seem to have compensated for the temperature-induced density decrease (Hansen et al, 2016). Seagliders reveal intense mixing and rapid warming of the overflow water at a secondary sill downstream of the FBC (Beaird et al., 2012). The general view, that the overflow entrains ambient water and thus roughly doubles in volume flux downstream into the abyssal Atlantic, has recently been challenged, based on year-long moorings in this mixing region (Ullgren et al., 2016). New unpublished data (summer 2016) show that a thin, very cold and likely fast flowing Ekman layer – at least intermittently – stretches farther south than previously anticipated; even farther south than the sections discussed in Ullgren et al. (2016). The mixing associated with secondary circulation at the edges of such an overflow plume was discussed. Instruments are presently moored in this location. Participants discussed whether or not to pursue a recently declined proposal, which was aimed at related questions, and which also involved numerical and physical models.

b) The Western Valley Overflow

A branch of overflow has been observed in a trench near Iceland – the Western Valley. Volume flux estimates based on moorings give 0.3-0.4 Sv of overflow water, but observations suggest that this overflow is not stationary. It was discussed whether Western Valley Overflow is composed of eddy trains or a stable flow. Seaglider observations reveal intense mixing near the foot of the Iceland slope, but cold water is not always present there. The Western Valley overfloW (WOW) is presently collecting more detailed observations of this overflow branch.

Other issues discussed

The workshop was rooted in the Norröna project. The vision is that the Norröna, presently involving the vessel mounted ADCP, the XBT casts and a Thermo-Salinograph should become a useful backbone for future studies. Moored current meter programs provide excellent temporal coverage over a wide range of time scales, but are limited to a finite number of sites, whereas vessels in repeat traffic provide excellent spatial information, but are limited to seasonal and longer time scales. Shipboard repeat hydrography is constrained in both space and time, but is key to our knowledge of water mass properties and transport. Satellite-based altimeters provide frequent gridded 2-dimensional SSH fields, but which probably are too spatially smoothed for studying processes on small scales. Participants discussed the need to combine datasets with different coverage in time and space to address many of our remaining scientific questions in this well-observed region. Several initiatives and collaborations started to emerge by the end of the workshop.

The group also discussed the potential to incorporate output from ‘realistic enough’ general circulation models, which can give a spatio-temporally and parametrically complete space, to improve the interpretation of our inherently under-sampled observations.

With fierce competition for project funding, the inclusion of aspects with socio-economic relevance should increasingly become a key driver for our scientific work in the region. We did briefly touch upon biological aspects, like the relation between the subarctic water masses in the FSC and the abundance of zooplankton, which fuels the entire marine ecosystem. Norröna has recently (December 2016) become a vehicle for the Continuous Plankton Recorder (CPR) survey, which might provide a branch into the biosphere, and potential inter-disciplinary studies.

Future Initiatives

The workshop discussions highlighted several areas of work and potential for future collaboration. In the immediate term, the following initiatives are emerging:

- An investigation into improving estimates of the geoid and thus altimeter geostrophic velocities by integrating data from the Norröna ADCP and XBTs and the satellite measurements.

- An investigation into the recirculation of the Southern Faroe Current in the FSC, by incorporating moored and Norröna ADCP data, to be initiated with moorings from summer 2017.

- Continued collaboration between those studying the overflows in the region, with the potential of submitting a revised proposal.

The previous RAFOS float studies (Søiland et al, 2008; Rossby et al, 2009) did not cover the flow in the FSC. A suggested longer-term initiative is to deploy sound sources within the Faroese Channels and thereby be able to follow the sub-surface RAFOS floats in these channels.

All participants agreed the meeting was a useful starting point to increase collaboration among the different research groups studying the Iceland-Faroe-Scotland region. With momentum sparked by discussions, all agreed that a follow up meeting would ensure the success of these collaborations, and hopefully culminating in joint publications and funding proposals. This would likely be in Bergen in September 2017.

Acknowledgements

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- The Scottish Government

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Appendices

Summaries from the presentations:

A1. Acronyms

ADCP	Acoustic Doppler Current Profiler
CTD	Conductivity-Temperature-Depth (sensor)
EOF	Empirical Orthogonal Function
FBC	Faroe Bank Channel
FC	Faroe Current
FSC	Faroe-Shetland Channel
ICES	International Council for the Exploration of the Sea
IFR	Iceland-Faroe Ridge
MOC	meridional overturning circulation
NAO	North Atlantic Oscillation (index)
SFC	Southern Faroe Current
SSH	Sea Surface Height
XBT	eXpendable BathyThermograph

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A3. Agenda

Monday 9. January at Havstovan

09.00 Intro (Tom Rossby)

Tom Rossby – the Norröna velocity program
Katelin Childers – Flow patterns in the NE Atlantic

Coffee

Hjálmar Hátún – Faroe Current and continuation towards the Arctic (retroflection)
Bee Berx – Interannual variability in the Faroe-Shetland Channel
Bogi Hansen – Atlantic Water passage through the Faroese Channels

12.30 Lunch

Jan Even Nilsen – Exchanges and Norwegian Atlantic Current (altimetry and SAR-doppler)
Visit from Jógvan Í Dávastovu, Smyril-Line
Charlie Flagg – the Norröna XBT program
Leon Chafik – the altimetric view of the region - space-time variability

Coffee

Anne-Britt Sandø – a modeler's perspective
Håvard Vindenes – The North Sea

Discussion

Tuesday 10. January

09.00 Overflow

Karin Margretha H. Larsen – Faroe Bank Channel Overflow
Detlef Quadfasel – IFR overflow
Jarle Berntsen – IFR modeling

Coffee

Nick Beaird (presented by Hjálmar Hátún) – Overflows
Henrik Søiland – RAFOS floats

Discussion – Issues and initiatives – please put on your thinking hats σ

12.30 Lunch

Discussion – continued

17.00 Workshop end

A4. The Norröna Project

Tom Rossby, Graduate School of Oceanography, University of Rhode Island

Introduction.

The motivation for the Norröna project is quite simple: to measure the inflow of all North Atlantic Water towards the Nordic Seas between Scotland, the Faroes and Iceland, and its spatial and temporal variability. This flow constitutes the Nordic Seas branch of the meridional overturning circulation (MOC), which plays a fundamental role – together with the atmosphere – in maintaining the mild climate of central and northern Europe. Helland-Hansen and Nansen (1909) gave the first truly comprehensive description of these flows, which more than 100 years later still strike a reader as remarkably accurate. The approach to monitoring this inflow was to install an acoustic Doppler current profiler (ADCP) in the Norröna, a high-seas ferry that operates out of Torshavn to Denmark and to Iceland on a weekly schedule. The data gathering started in 2008. As the database grows we will be able to assess the strength and variability of the MOC in this region, and together with other observational programs interpret these in a larger geophysical sense. But from a climate research point of view one also wants to know the heat flux. To address this need the Norröna project has also been taking XBTs on a monthly schedule, 12 each across the Faroe-Shetland Channel (FSC) and along the Iceland-Faroe Ridge (IFR). The left panel of Figure 1 shows the transits used in the following figures. Each white dot represents an ADCP velocity profile.

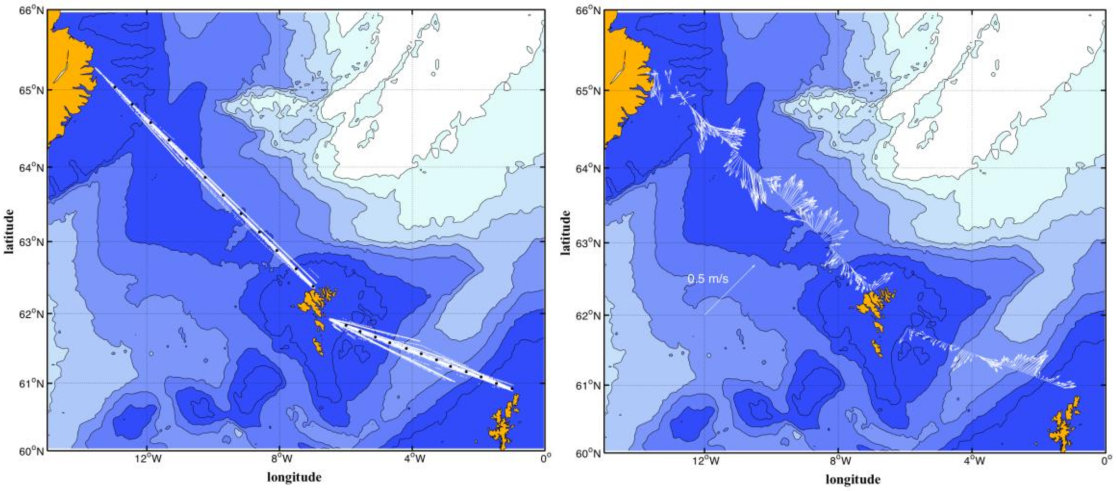

Figure 1. The left panel shows the location of all ADCP profiles taken across the FSC and IFR. The 12 black dots in each section indicate the XBT sites. The right panel shows typical velocity vectors from a transit in summer 2015.

After a delayed start due to a severe problem with bubble drawdown that block with the ADCP acoustic beams, we have been collecting velocity data since spring 2008, and especially since February 2009 when the ADCP was repositioned close to the centerline in a streamlined fairing, and potentially further improved by the two chines or vortex generators that help lift clear water towards the ADCP. The focus of the program has been on the longer time scale flow patterns and their variability. The Norröna route varied a bit in the first years (Rossby and Flagg, 2012; Childers et al., 2014), but on her transits to and from Hirtshals (and earlier Hanstholm) in northern Denmark she almost always passes just north of Shetland. The right panel of Figure 1 shows velocity vectors from a transit in summer 2015. Even though it is only a snapshot it shows the Scotland Slope Current clearly. One also sees a flow south along the Faroe slope in the FSC. The vectors are less organized over the IFR where there is a lot of eddy activity associated with the warm water inflow. All ADCP and XBT data can be downloaded at our Stony Brook website: http://po.msrc.sunysb.edu/Norrona.

A brief summary of results to date.

We begin with the FSC. The left and right panels of Figure 2 show the annual mean velocity normal to the ship track (essentially along channel) and temperature. The black lines show the integrals of volume and temperature transport (both starting at the Faroes end). The net transport between the surface and the 4°C isotherm equals 2.2±0.3 Sv. The temperature transport is 93±14 TW (terawatt). The uncertainty of the integrals reflects variations in transport from year-to-year. These fluxes are significantly larger than what Rossby and Flagg (2012) reported for the first few years of operation, principally due to a weaker flow south on the Faroes slope in more recent years.

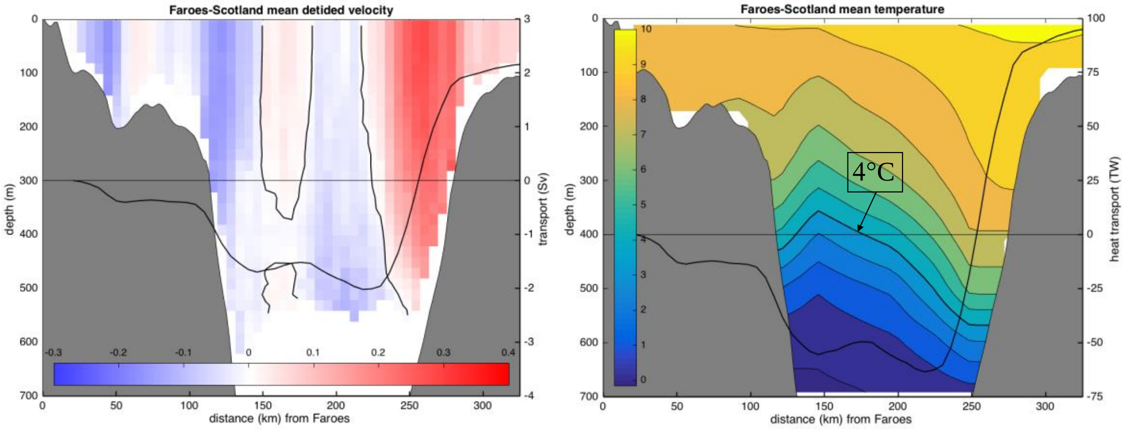

Figure 2. The left and right panels show the annual mean velocity normal to the ship track (essentially along channel) and temperature. The black lines show the integrals of volume and temperature transport (both starting at the Faroes end). Red and blue colors represent flows towards and from the Nordic Seas in ms^{-1}. The zero contour is highlighted.

The IFR section has been a much greater technical challenge due to the above-mentioned bubble program limiting us to useful ADCP data collection during the summer months when sea swell is down. The two panels in Figure 3 parallel those of Figure 2 except that the left panel shows mean velocity only for the summer months. The right panel of temperature is an annual average. The top-to-bottom net inflow of 4.5 ±0.7 Sv is highly structured with a shallow, but well-defined inflow (towards the Nordic Seas) over the western valley at 150 km (from Iceland); this is the western end of the Iceland-Faroe Front (IFF). But this flow turns southeast and angles back towards the Atlantic (the blue velocities between roughly 170 and 260 km) before finally entering the Nordic Seas at the deeper points of the IFR at 300 and 350 km. There is also a well-defined flow along the upper Faroe shelf, which we presume is part of a circum-Faroe circulation (it can be seen as a southward flow at 40 km in Figure 2).

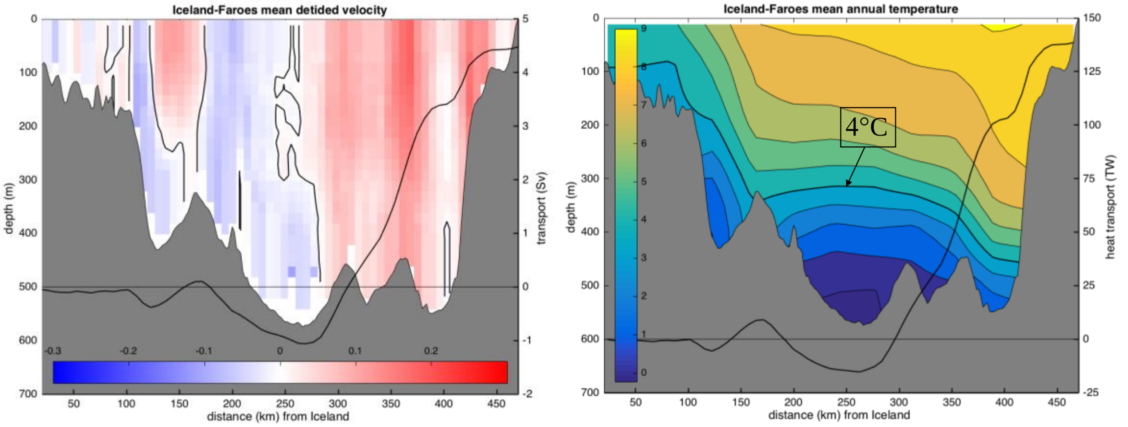

Figure 3. The left and right panels show summer mean velocity normal to the ship track (essentially along channel) and annual mean temperature. The black lines show the integrals of volume and temperature transport (both starting at the Iceland end). Red and blue colors represent flows towards and from the Nordic Seas in ms^{-1}. The zero contour is highlighted.

The repeat sampling by the Norröna also gives us much information on variability. One classical approach is to simply map out the eddy kinetic energy field (EKE). These are shown for the two sections in Figure 4. Both sections show decreasing EKE levels from the surface down, consistent with these being significantly baroclinic. That this is the case even in the Scotland Slope Current means that this current can vary considerably in time. Interestingly, there is an increase of EKE at 600-700 m depths on the Scotland side. The IFR EKE includes only summer months. We see a high EKE level where the IFF first crosses the Norröna route between ~130 and 230 km. This is very likely due to the front moving in over and back away from the route. But where the IFF turns north at 300 and 350 km the EKE is barely elevated pointing to stabilization by the bathymetry. If this stability can be further verified, this might be a good place for moored instrumentation to monitor inflow variability. Note also the high EKE level at depth in the FSC. At first I thought it was due to few data, but it is distinctly located on the Scotland side. This is worth further study.

Another view of temporal variability (for the FSC only) is to estimate the seasonal amplitude of transport and how transport changes from one year to another. These are shown in Figure 5. These are shown here for workshop discussion; they are not ready for publication. The left panel shows the seasonal cycle of transport for the entire FSC (surface to 4°C) in black and for the Slope Current only in red. Skagseth et al. (2004) argue that this seasonal cycle is wind-driven. The timing of the annual cycle agrees well with Berx et al. (2013), but the amplitude seems too large. This needs to be investigated further. The right panel shows simple annual averages stepped forward one year at a time (no data for 2013). The black line shows a non-monotonic increase in transport over the duration of the program. These figures should be viewed as exploratory, not definitive results.

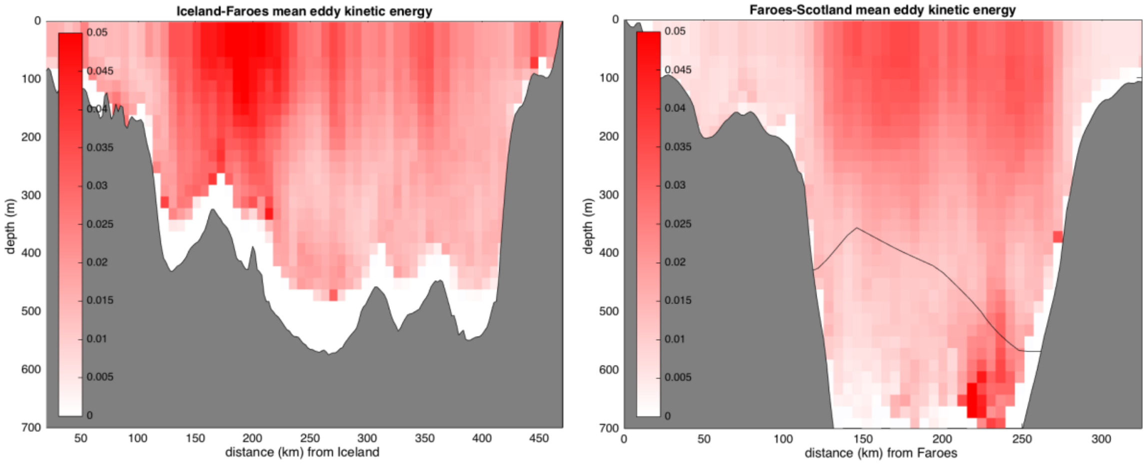

Figure 4. The left and right panels show EKE for the IFR and FSC, resp. The scales show EKE in $m^2 s^{-2}$.

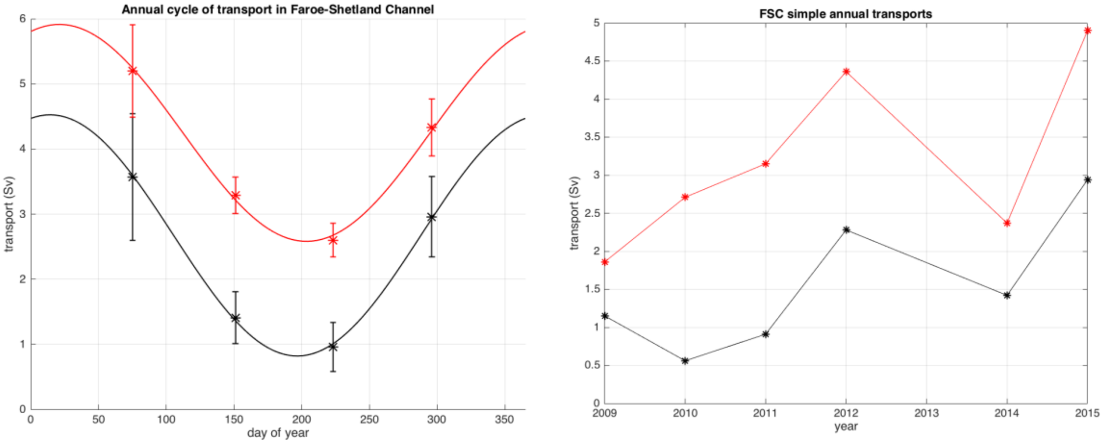

Figure 5. The left panel shows a first attempt at estimating the seasonal cycle of transport in the FSC. The right panel shows simple annual averages of transport in the FSC. In both panels the black line pertains to the entire FSC (to the 4°C isotherm); the red line applies to the Scotland Slope Current.

Perhaps a more instructive view of Scotland Slope Current variability might be to consider only complete sections across it in order to get its mean velocity at each time and how these vary. The left panel in Figure 6 shows the average velocity of each section in the top 200 m between the 100 m and 1000 m isobaths on the Scotland side. Even though these are section means, there is quite a lot of scatter, in fact even a few cases of negative flow. We will have to look at other sources for corroboration, but it would appear that these are times when the Slope Current separates from the slope (cf. Chafik et al., 2012). Geostrophy requires that a separated Slope Current have a pool of deep warm water between it and the Scotland slope, a condition that would support an anticyclonic circulation, and thus plausibly a southward flow along the Scotland slope. The right panel shows the probability distribution. The main point of this figure would be that the Slope Current does indeed vary considerably.

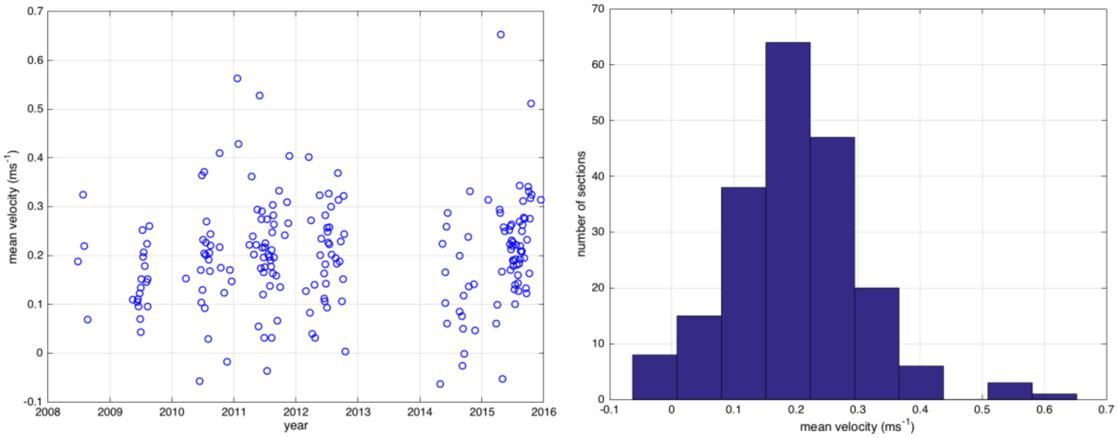

Figure 6. The left panel shows mean velocity in the top 200 m of the Scotland Slope Current between ~100 m and the 1000 m isobath. The right panel shows the corresponding probability distribution.

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A5. Pathways of Atlantic Water over the Iceland-Faroes-Scotland Ridge

Katelin Childers, Stony Brook University

This presentation was based on results from Childers et al., 2015.

The North Atlantic Current bifurcates southeast of the Reykjanes Ridge (RR) into poleward flowing branches on each side. The eastern branch, which becomes the major source of all water entering the Nordic Seas (Orvik and Niiler, 2002) is strongly influenced by topography. Waters entering through the Iceland Basin west of Hatton Bank will largely cross the Iceland Faroes Ridge (IFR) into the Norwegian Sea, but some will split off through the Banks towards Scotland. The remainder will curve west following the Iceland slope and the RR. To the east, water with a strong Mediterranean component enters the Rockall Trough from the south, potentially as part of a northward flowing shelf edge current (Reid, 1979; Orvik and Niiler 2002; Iorga and Lozier, 1999), however McCartney and Mauritzen (2001) provide a comprehensive overview and synthesis of the hydrographic literature of the northeast Atlantic, and in their review make it quite clear that most water entering the Faroe-Shetland Channel must come from the North Atlantic Current (NAC) and not the Mediterranean outflow. We support this conclusion using data from hull-mounted acoustic Doppler current profilers (ADCP) in two vessels, the M/V Nuka Arctica and M/F Norröna. These operate along four different routes between Scotland, Iceland, and Greenland (Figure 1) and are used to map the mean flow of water in the top 400 m of the northeastern North Atlantic.

Data is taken from a hull-mounted 150 kHz ADCP on the Royal Arctic Lines M/V Nuka Arctica, which profiled up to 400m deep from 1999-2002, and a 75 kHz ADCP on the M/F Norröna reaching to about 500-600 m from 2008-2012. Each vessel followed one of three regular routes near the ridge. Data from the ADCP's 3-second ping ensembles were averaged into 5 km lateral by 8 m (Nuka Arctica) and 20 m (Norröna) depth bins, and route transport was calculated as the velocity normal to each of the four ship routes times the area of each bin along the route. To construct the transport integrals, westward integrations were started start just inshore of the Slope Current (approximately 100 m isobath) and include all flow in the top 400 m. Transport estimates are most robust along the C and G routes and less so over the less frequently sampled D route.

We show that along the southern boundary of the observational domain, poleward flow occurs in the central Iceland Basin (~3 Sv) and along the western slope of Hatton Bank, (~2 Sv) and in two other concentrated flows, one near 400 km and another at the Shetland Slope, both about 1.5 Sv. The integral peaks at ~ 9.5 Sv before decreasing to ~8.5 Sv due to southward flow along the eastern RR (Chafik et al., 2014). The transport uncertainty is 0.94 Sv. Moving northward, the Slope Current strengthens to ~3 Sv and maximum poleward flow barely reaches 8 Sv at about 600 km before decreasing somewhat towards the Iceland Slope. The total transport uncertainty of integration is 1.58 Sv along the D route. By the Norröna route, the Slope Current has increases to 3.1 Sv in the top 400 m, but there is a southward flow on the western side of the Faroe-Shetland Channel such that the net inflow in the top 400 m is just under 2 Sv. The workshop provided considerable discussion about the sources and fate of the southern flow to the west of the Faroes and plans are underway to organize observational programs to more clearly identify its behavior.

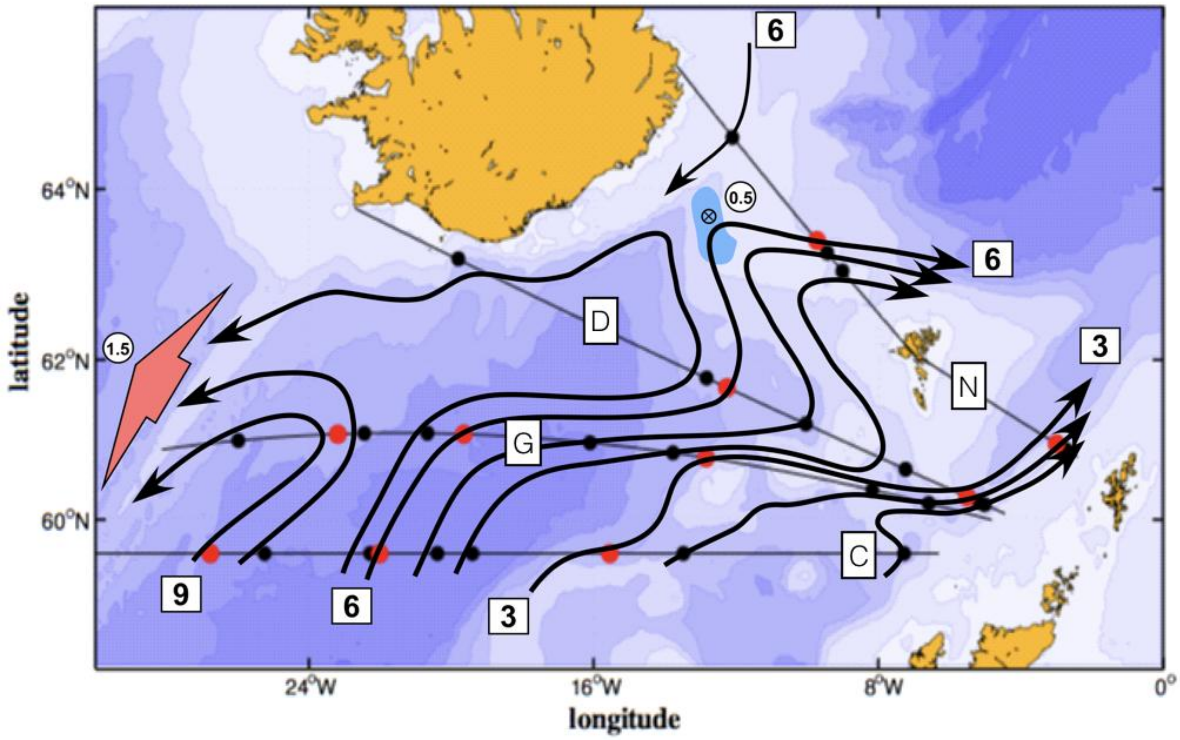

Fig. 1. Cumulative transport in Sv (beginning on the eastern side) for the C, G, D, and N(orröna) routes. Black dots indicate each Sv change in cumulative transport (summing from east to west along each route) and red dots indicate each third Sv. The wide pink arrow indicates the flow across the RR and the blue area indicates schematically the loss of overflow water at 400 m depth

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A6. The Southern Faroe Current

Hjálmar Hátún, Faroe Marine Research Institute

It is now acknowledged that oceanic heat anomalies from the North Atlantic Ocean have a profound impact on Arctic temperature and ice cover (refs). Through stratosphere-troposphere coupling and atmospheric planetary-waves, Arctic warming will impact the polar vortex, the jet stream and thus weather at lower latitudes – a so-called teleconnection.

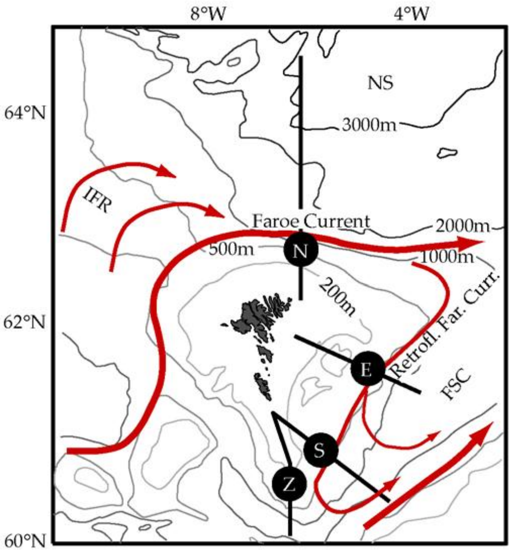

Figure 1. Topography of the Fareo Plateau and surroundings showing the Iceland-Faroe Ridge (IFR), the Nordic Seas (NS) and the Faroe Shetland Channel (FSC). Red arrows indicate inflow of Atlantic Water. Black lines indicate standard sections, were each is labelled with a letter. ADCP mooring sites are along these sections.

The oceanic heat transport across the Greenland-Scotland Ridge (GSR), from the North Atlantic to the Nordic Seas is transported pole-ward in two main current branches – the eastern and western Norwegian Atlantic Current (NwAC). The eastern branch has a more direct connectivity to the high Arctic, while the western branch transports more heat into the central Nordic Seas (ref). The largest GSR Inflow of Atlantic water takes place between Iceland and the Faroe Islands (ref. Bogi), and a significant portion of this Faroe Current (FC) transport crosses over to the eastern, Inner or Slope branch of the NwAC just northeast of the Faroe Plateau through the Southern Faroe Current (SFC). Recent studies using drifter and hydrographic data together with satellite altimetry directly implies that the Iceland Faroe inflow of Atlantic Water has more importance for the Barents Sea and Arctic Ocean than previously assumed, and that we cannot consider the two branches of northward flowing Atlantic water in the Nordic Seas as two independent flows (refs. Roshin, Rossby, 2009). Mid-depth floats revealed strong tendency for floats to follow the Faroe Plateau into and across the Faroe-Shetland Channel (FSC), and then along the continental slope northeast toward the Lofoten Basin (Søiland 2008). The principal reason that so many floats crossover to the inner branch appears to be that at ~200 m depth they ‘‘feel’’ the bathymetry more so than the more rapidly flowing surface waters, inducing them to turn toward the FSC rather than follow the surface waters (Rossby 2009). Upstream of the separation point on the northeastern corner of the Faroe Plateau, the FC ‘‘leans’’ against the bottom (Rossby et al., 2009), and meridional shifts of the FC are therefore expected to have an impact on how large portion of this flow joins the eastern NAC, and thus likely reaches the Arctic.

Only a weak seasonality has been reported in the Atlantic water flows across the GSR, but the SFC has a very clear seasonal signal after 1995, with a maximum in February-April and an amplitude of

~0.6 Sv (Hátún, 2004). A one-year long current series (summer 1999 to summer 2000) in the FSC (mooring E, Fig. 1) verifies this seasonality with a strong current peak (25-30 cm/s) during March. This current velocity is on the same order of magnitude as the core-current north of the Faroes, confirming that a large fraction of the FC may turn into the FSC during spring. The southwestward flowing SFC furthermore seems to follow both the decadal scale and the seasonal variations of the wind stress curl over the Nordic Seas, which again is closely related to the North Atlantic Oscillation (NAO) (refs). Both series show a characteristic 5-year cycle, a maximum in February-April and a clear regime change in 1995-1996 (Hátún. 2004).

In a study combining altimetry and hydrography, Chafik (2012) showed that a part of the southwestward flowing SFC is carried in cyclonic cold-core eddies, which pinch off from the Norwegian Sea gyre. The entry of such eddies will lift the interface between the relatively warm Atlantic water above, and the colder Norwegian Sea Deep Water (NSDW) and Modified East Icelandic Water (MEIW) below, which in turn can be observed as a depression in the sea surface height (Chafik 2012). Using altimetry data, he showed that for positive phases of the NAO, the surface circulation tended to be strongly bathymetrically constrained with increased flow into the FSC. The negative phases of the NAO are associated with a regional weakening of the wind-stress curl, which leads to a contraction of the Norwegian-Sea gyre and a linked northward migration of the FSC recirculation, which in addition deflected the path of the Shetland-slope current.

The above discussed dynamics is captured by the first Empirical Orthogonal Function (EOF) mode of the sea surface height over the study region (preliminary study by K.M.H. Larsen, Fig. 2a). Significant correlations were found between the principal component associated with the first SSH mode (Fig. 2b) and the along-slope current component (200 m depths) both in the FC and in the FSC. Generally depressed sea levels in the Norwegian Sea and in the FSC are lead to increased currents from the FC to the FSC.

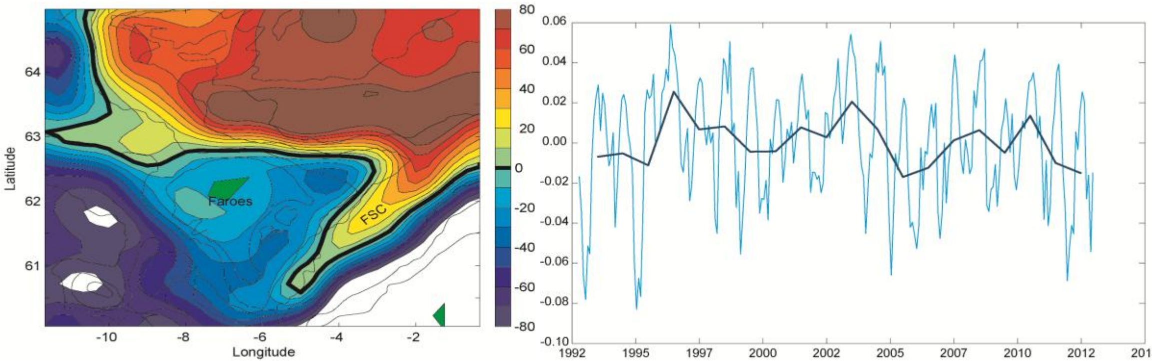

Figure 2. EOF analysis of the sea surface height. Left panel: the first spatial EOF mode. Right panel: The associated principal component time series

Acoustic Doppler Current Profiler (ADCP) observations from the ferry m/s Norröna along a section across the FSC has provided a new and somewhat controversial perspective to the oceanography of the FSC. Rossby and Flagg (2012) identified a strong southward flow along the Faroe slope at about 300-500 m depths, which led to a nearly zero total transport of Atlantic water through the channel. New monthly XBT sections and updated ADCP observations from this ferry (unpublished) show *i*) large vertical undulations of the main thermocline/pycnocline within the channel, and *ii*) a significant negative correlation between the southward flow along the Faroe slope and the northward flow in the Shetland-slope current (presented by Flagg).

Due to the obvious importance of the flow variability from the FC to the SFC, current observations from the northeastern part of the Faroe Plateau are desirable. A preliminary study showed that all surface drifters shifting south from the FC into the SFC did so along a bathymetric escarpment near 4°W on the northeastern extension of the Faroe Plateau. After having crossed this 'point of no return', they did not shift back into the western NwAC branch. The lower 'foot' of this topographic escarpment avoids trawling, and a pilot experiment demonstrated the feasibility of deploying current moorings there.

In the planned project, the Faroe Marine Research Institute (FAMRI) will deploy two ADCPs in the NE corner of the Faroe Plateau, immediately north and south of the bathymetric escarpment for a year. The following positions will be used: x1, y1 and x2, y2.
It also turns out that the m/s Norröna line nearly coincides with both a long-term hydrographic section (the Nólsoy-Flugga line), and altimetric track (the now terminated Topex Poseidon/Jason track, presently occupied by the xxx satellite). The Marine Lab in Aberdeen (MARLAB) will complement the FAMRI initiative, by deploying three ADCPs – one in the core of the SFC and one the altimetry track, one in the core of the Shetland-slope current (also on the altimetry track), and a third to be decided.
A more detailed investigation of the association between the flow field and hydrography will be performed, based on data from a Seaglider from MARLAB.

Complementing the planned project, a description of the pycnocline variability under the FC, and thus the meridional position and the degree of bottom "leaning" of this current will concurrently be obtained from the PIES and the Seaglider along section N (projects FARMON and Blue Action). Together, this should give a better understanding of important links between atmospheric forcing, the dynamics of the FC and the cross-over in the FSC to the eastern NwAC branch and thus the oceanic heat transport into the Barents Sea and the Arctic Ocean.

A7. Inter-annual variability of Atlantic Water in the Faroe-Shetland Channel

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The Shetland Branch of the exchanges between the Nordic Seas and the Atlantic Ocean is one of the main pathways for warm, saline Atlantic Water (AW) to reach the Polar Regions (Figure 1). The first ocean observations in the Faroe-Shetland Channel date back to 1893, when multi-disciplinary surveys were initiated by fisheries oceanographers. Regular hydrographic surveys have since continued on a more or less annual basis. In the 1990s, moored Acoustic Doppler Current Profilers (ADCPs) were deployed to collect direct current meter measurements of the AW transport, ringing in the *Transport Mooring Array* (TMA) era (Figure 1).

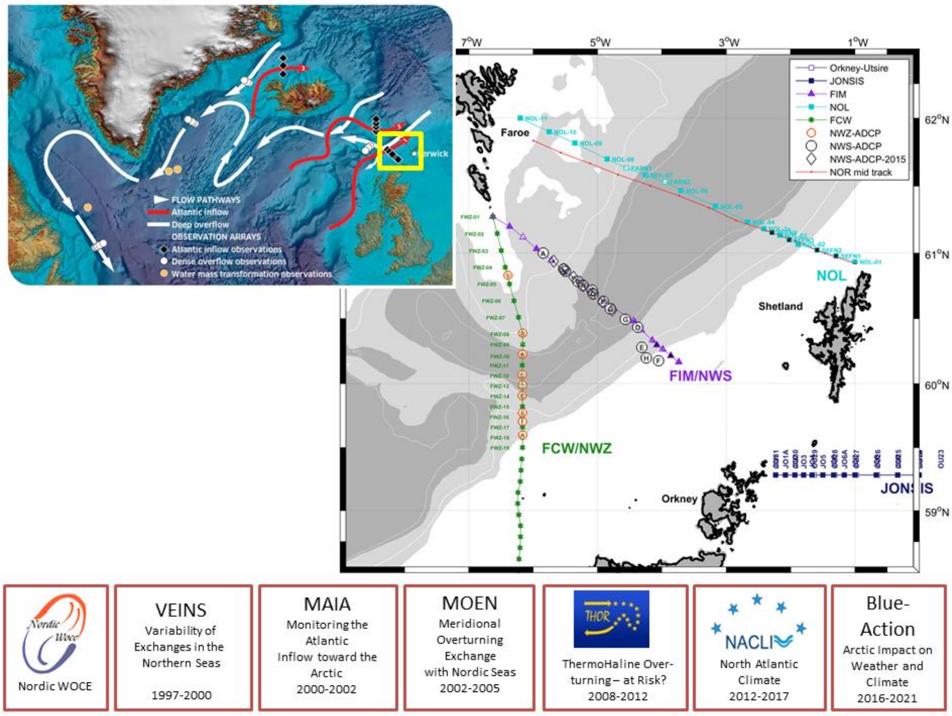

Figure 1. The Faroe-Shetland Channel Transport Mooring Array: map shows bathymetry (shading in 3 categories: white < 200 m, light grey >200 m but <800 m, and dark grey > 800 m), key hydrographic sections (JONSIS = Joint North Sea Information System, FIM = Fair Isle-Munken, NOL = Nolso-Flugga, FCW = Faroe-Cape Wrath), and historic mooring positions (NWS = Nordic WOCE S-section, NWZ = Nordic WOCE Z-section). The high seas ferry Norröna track (NOR mid track) is also shown).

The Faroe-Shetland Channel TMA (Figure 1) is a key part in monitoring the Shetland Branch, and provides invaluable data to improve our understanding of the variability of this flow. The TMA highlights the importance of international collaboration and the complementary nature of project-based and government funding to sustain ocean observations. The array consists of repeat hydrography surveys (now 3-6 times per year), moored current meters and Conductivity-Temperature-Depth (CTD) sensors, which are enhanced with satellite altimeter observations.

The currents in the Faroe-Shetland Channel are complex, as many others will highlight in their contributions in this report. In the surface layers (shallower than approx. 500 m), the AW derives from two pathways: one mainly following the shelf edge on the UK-side of the channel, and one from the recirculation of the Faroe Current in the FSC. Berx et al. (2013) published a new methodology to estimate the AW transport from both pathways of the Shetland Branch by combining the hydrography, moored current meters and satellite altimeter. The revised transport estimate of AW entering the Nordic Seas via the Faroe-Shetland Channel was 2.7 Sv (1 Sv = 10^6 m^3 s^{-1}). This had a seasonality of approx. 0.7-0.9 Sv (depending on the calculation method), and no long term trend (Figure 2). The mean relative heat transport was 107 TW, and the salt transport was 98 x 10^6 kg s^{-1}.

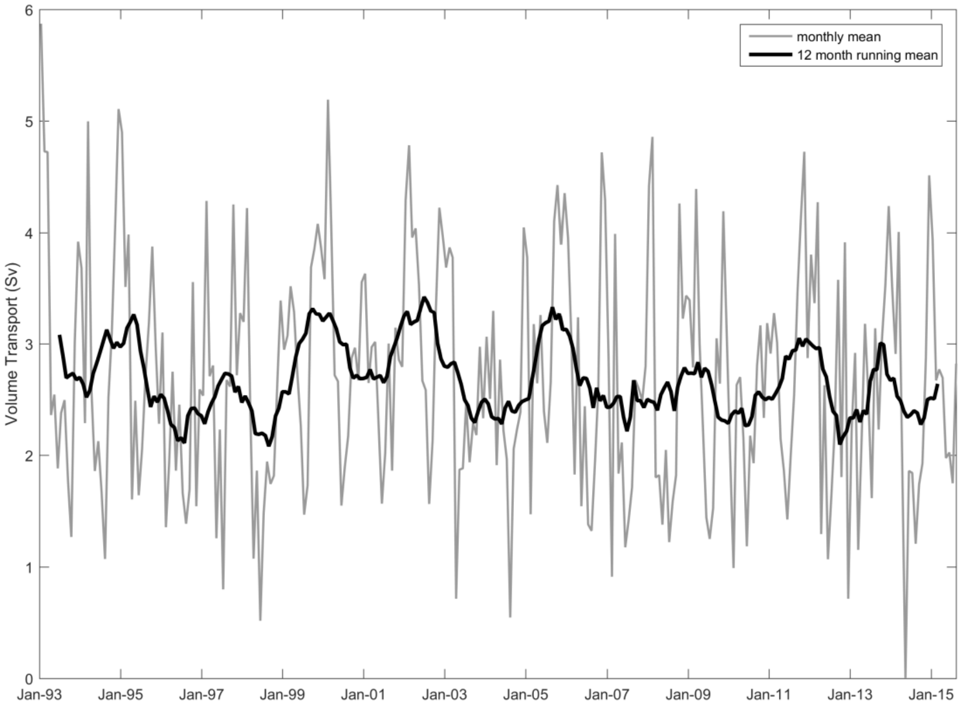

Figure 2. Volume transport of Atlantic Water (AW) in the Shetland Branch, calculated from satellite altimetry (see Berx et al. (2013) for details on the method).

For the heat and salt transport quantities, however, there was no associated time series. Recently, scientists have been working on how to calculate time series of these based on combining the repeat hydrography with satellite altimeter observations of geostrophic velocity. Increases in both temperature and salinity have been observed, and a possible long term trend in the relative heat and salt transports can be expected. Preliminary results (Figure 3) show no statistically significant trend in the transport weighted temperature anomaly.

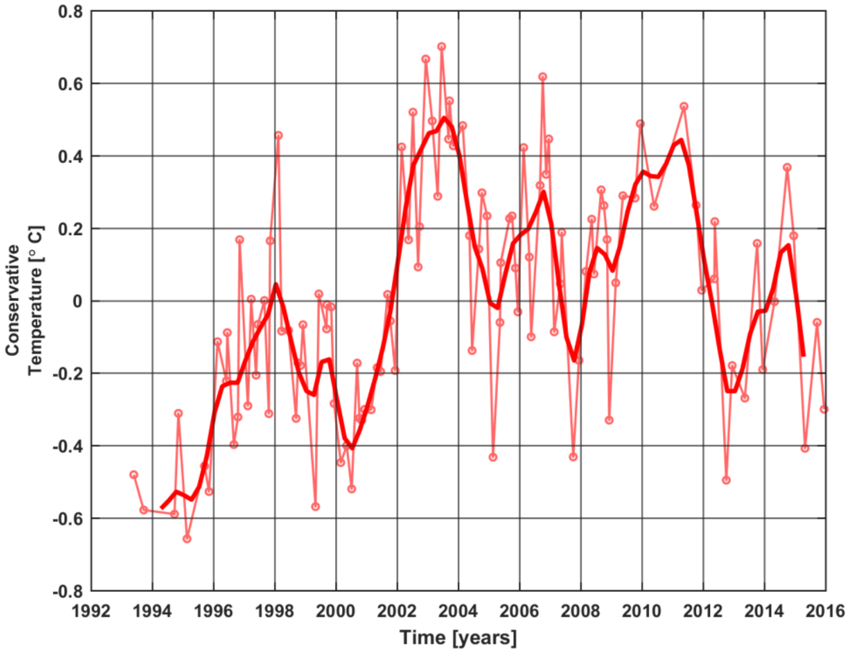

Figure 3. Transport weighted temperature anomaly [°C] above 5° C isotherm through the FIM hydrographic section in the Faroe-Shetland Channel. The time series includes 111 repeated hydrographic sections for a period between May 1993 and December 2015. The anomaly has been calculated by removing the seasonal mean, and is weighted by of the net volume transport. Red circles, connected with a thin line, are observations from individual sections, bold line shows one year running mean.

Sherwin et al. (2008) in previous studies of the inter-annual variability of the AW circulation in the Faroe-Shetland Channel suggest that approx. 50% of the AW transport variability is attributable to wind stress variations, while the remainder is assumed to be driven by the north-south pressure gradient. More recently, Chafik (2012) linked inter-annual variability of the local circulation to changes in the wider North Atlantic weather forcing; with a low North Atlantic Oscillation (NAO) index resulting in a strong influence of the wind field in the FSC on local dynamics.

Work is currently in progress to refine the transport time series of volume, heat and salt of Atlantic Water in the Shetland Branch, and to subsequently relate variability of these time series with changes in the basin-scale drivers. These linkages will then be tested using the VIKING20 model to further investigate the importance of the Faroe-Shetland Channel in the Nordic Seas exchanges.

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A8. Atlantic water flow through the Faroese Channels

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The Faroese Channels is a system of channels linking the Faroe-Shetland Channel (FSC) to the Faroe Bank Channel (FBC) through the Wyville Thomson Basin (WTB). The deep parts of this system are dominated by cold waters from Arctic regions that exit the system as overflow through the FBC and across the Wyville Thomson Ridge (WTR). The upper layers, in contrast, are dominated by warm and saline water masses from the Atlantic. In addition to the Atlantic inflow from the west, the FSC receives Atlantic water from north of the Faroes. This current, termed the Southern Faroe Current (SFC), flows southwestwards over the Faroese side of the FSC, but there are conflicting views on its further fate. In one scheme (Figure 1a), originally indicated by Helland-Hansen and Nansen (1909), the SFC re-circulates within the FSC. The other scheme (Figure 1b), suggested by Dooley and Meincke (1981), has a large part of the SFC continuing through the FBC and, according to Rossby and Flagg (2012), it may circulate the Faroe Plateau.

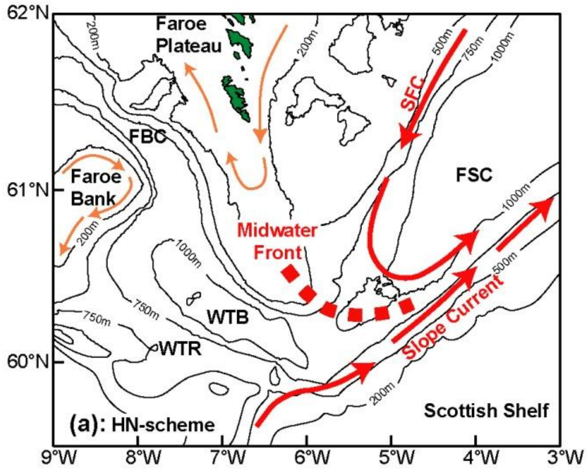

Figure 1. The two suggested circulation diagrams for the further fate of the SFC and the link of the surface circulation between the FSC and the FBC: **(a)** where the SFC re-circulates more or less completely within the FSC, after Helland-Hansen and Nansen (1909) (the HN-scheme); or **(b)** where the SFC splits and roughly half of the water continues through the FBC while the rest re-circulates within the FSC, after Dooley and Meincke (1981) (the DM-scheme).

By combining the observational evidence from ship-borne hydrography, moored current measurements, surface drifter tracks, and satellite altimetry, it is found that the SFC is totally re-circulated within the combined area of the FSC and WTB, except possibly for a small release in the form of eddies. No evidence is found for a continuous flow of Atlantic water from the FSC to the FBC over the Faroe slope. Rather, there seems to be a persistent flow of Atlantic water from the western part of the FBC into the FSC that joins the Slope Current over the Scottish slope.

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A9. Exchanges and the Norwegian Atlantic Current (altimetry and SAR-Doppler)

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The warm and saline Atlantic Water entering through the IFR and FSC transports heat to the Arctic, maintains the ice-free oceans and regulates sea-ice extent, influences the region's relatively mild climate, and is the northern branch of the global thermohaline overturning circulation. Heat loss in the Norwegian Sea is key for both heat transport and deep water formation in this branch. The exchanges, flow patterns and strength, and hence the horizontal distribution of AW in the Nordic Seas, are strongly governed by topography and large scale wind forcing (Nilsen et al., 2003; Furevik and Nilsen, 2005; Sandø et al., 2012). There is also strong eddy activity in particular parts of the region.

The AW flows in the Norwegian Atlantic Current, which is a two branch system with extensive eddy activity between the two branches. The two branches are normally considered to stem from the IFR and FSC inflow respectively, but the particularly strong eddy activity in the FSC and the Southern Faroe Current (SFC) makes this separation somewhat artificial. A relevant question is how much water is exchanged and under which conditions is the exchange enhanced. This has consequences for where in the northern regions the transported heat and salt will have most of influence (e.g., in the Barents Sea or Arctic Ocean through the Fram Strait).

Remote sensing such as altimetry and ASAR Doppler velocity estimates can shed light on this question, both in the FSC and further north in the Norwegian Sea. Studies have applied altimetry to map surface currents (Raj et al., 2015b; Raj et al., in prep.) and eddy activity (Raj et al., 2015a; 2016) in the Norwegian Sea. These studies have shown that the speed and topographic steering of the currents are enhanced under intensified cyclonic atmospheric flow over the Nordic Seas. In particular SFC is clearly pronounced and shows a continuous current across the FSC, connecting the Faroe Current and the Norwegian Atlantic Slope Current (Fig. 1a).

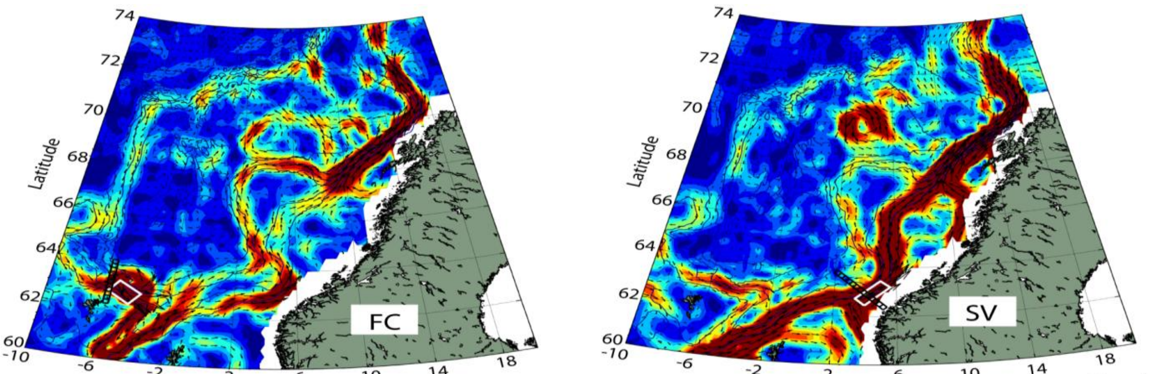

Figure 1: Composite maps (1993-2010) of the difference in the mean high and low component velocities (speed in colors). a) strong Faroe Current; b) strong Svinøy Current. From Raj et al. (in prep.).

The ocean's surface circulation relates to the ocean's mean dynamic topography (MDT) through geostrophy, which yields the long-term averaged strength of the ocean currents, i.e., the mean circulation of the ocean (e.g., Knudsen et al., 2011). The precise knowledge of the geoid height, together with the mean sea surface (MSS), known within centimeter accuracy (Schaeffer et al., 2012), enables us to compute the mean dynamic topography (MDT) of the ocean. The geoid is the equipotential surface of Earth's gravity field. More accurately it is the sea surface in the absence of winds, tides, and currents, only influenced by gravity (e.g., Raj, 2017). Given remote sensed instantaneous SSH, the surface velocity can be approximated from gradients in absolute dynamic topography (ADT). In practice ADT is estimated as the difference between the MDT and sea level anomalies (SLA; the difference between SSH and MSS).

However, the MDT has been shown to yield too weak gradients in regions of swift currents such as the IFR. Figure 2 shows an example of this: The surface ADT has very little variations across the section, while the in situ hydrography show more changes of the gradients, resulting in spurious features in the deeper velocity as velocities are integrated from the surface and down through the density field. The possibility to compare altimetry derived surface velocities, as well as calculate alternative more detailed local MDT using in situ ADCP (Norröna) sections across the FSC (and IFR), will be investigated further in this consortium.

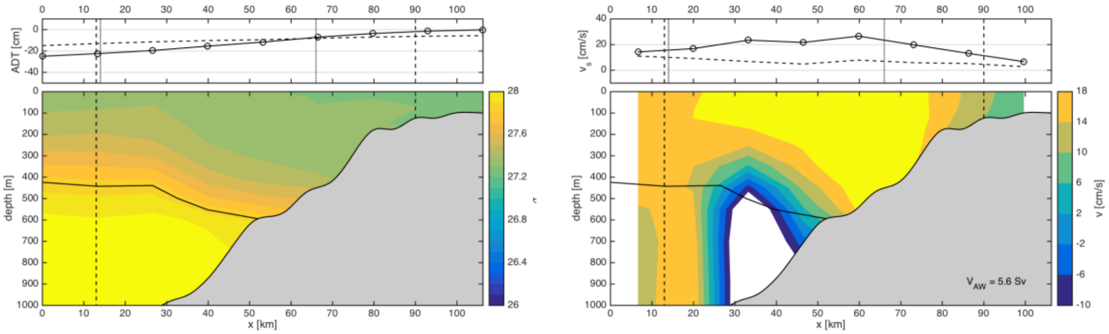

Figure 2: Mean (1993-2015) density (a) and velocity (b) sections in the Shetland Current, based on altimetry and climatological hydrography. Upper panels show ADT and surface velocity, respectively, for strong (full) and weak (dashed) surface current situations. Black contour in section represents the mean 35 isohaline. From Raj et al. (in prep.).

Advanced Synthetic Aperture Radar (ASAR) can provide estimates of surface velocities through the utilization of the Doppler effect on the reflected signals (Hansen 2011; Hansen et al., 2012). The provision of surface velocities for specific regions and time periods, requires extensive signal and image processing, a work that is on-going at NERSC. An example 2007–2011 climatology of zonal surface velocities is shown in Figure 3. Due to the angle of the beam and orientation of satellite tracks, the zonal velocity component is more precise than the meridional. A validation against in-situ current meter velocities in the Svinøy Section, shows agreement of the mean within a few centimeters (Hansen et al., 2012), while altimetry estimates are off by an order of 10 cm there. Another advantage of ASAR is that it is more reliable in near coastal regions than altimetry. We believe there is strong potential for additional mapping of the current patterns in the IFR and FSC by Doppler velocities.

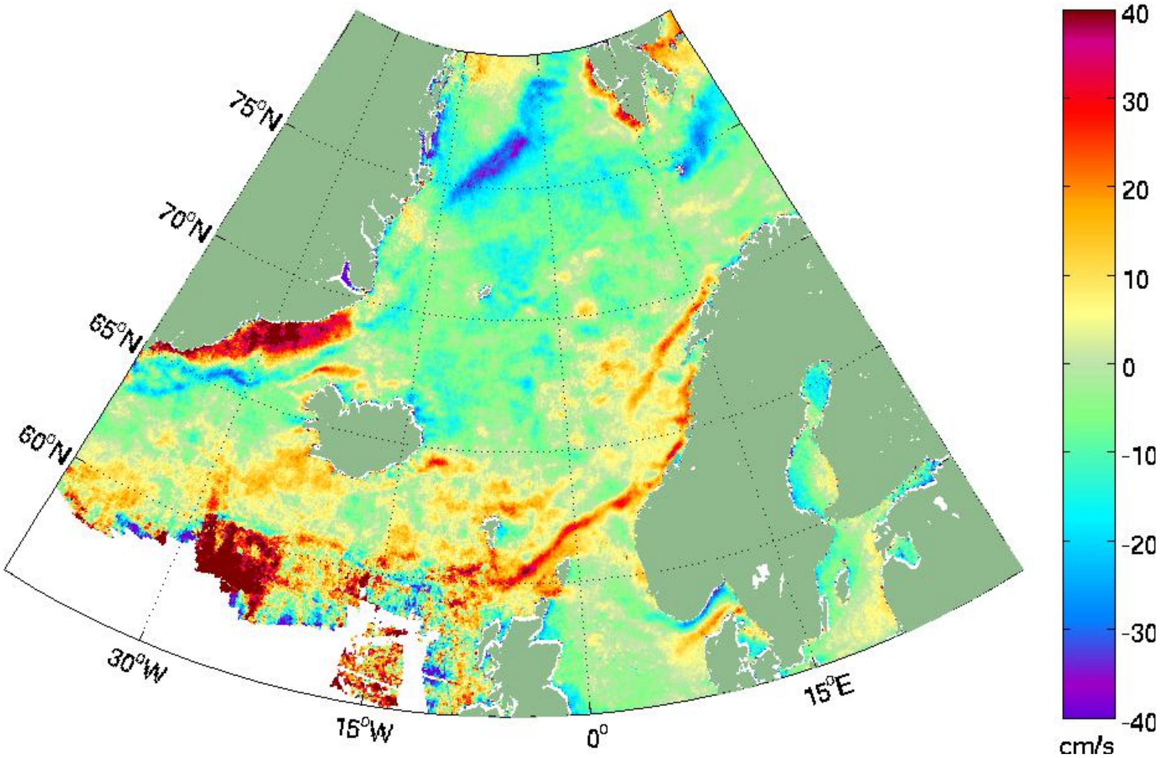

Figure 3: Climatology (2007-2011) of zonal velocity from ASAR Doppler. From Hansen et al. (2012).

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A10. Status of the Norrona Data Collection

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The Norrona Project supports three instrument systems on the ship, the OS 75 kHz ADCP, the AXIS automatic XBT launcher, and the thermosalinigraph (TSG). A fourth system, a continuous plankton recorder (CPR), has recently been added to this suite by the Sir Alister Hardy Foundation.

The ADCP was first installed in 2006, but immediately ran into problems that prevented any data collection. After diagnosing the problem to be due to bubble sweepdown which caused a near-permanent cloud of bubbles in front of the transducer, Smyril Lines allowed us in 2008 to install a streamlined bubble fairing. This lowered the ADCP about 0.2 m below the hull and greatly alleviated the problem although it did not totally solve the interference, especially in any significant seaway. ADCP data collection has continued under this arrangement but the data coverage has suffered, especially under wintertime conditions along the Iceland-Faroes leg.

As a result of the continuing bubble problem we have been searching for a method to improve the data collection for several years. One approach that was recommended by the ship's designers and others was to move the ADCP from its position amid-ships to a place on the ship's skeg. The Norrona is a twin-screw vessel with large propellers separated by a rather massive skeg that extends below the aft portion of the hull. The thinking is that the bubble cloud that floats along the bottom of the ship would be drawn up along the hull and into the propellers leaving the bottom of the skeg in fairly clear water. With the intent of improving the ADCP's performance and again with Smyril Lines' permission, we engaged marine designers to come up with a new location for the ADCP transducer as far aft as possible. As a result, the ADCP was moved to a new location on the ship's skeg where the skeg extends below the hull by 3 to 4 meters. The ultimate assessment of this new location will be whether it improves the data collection during less than summertime weather and that will take some time.

The automated XBT system makes use of the AXIS system developed by engineers at Woods Hole Oceanographic Institution. The mechanical part of the AXIS system consists of a circular cylinder that holds 12 XBT probes such that the probes can individually be moved into a position over a launch tube and a pin pulled to deploy the probes on command. Commands are sent to the AXIS over an Iridium satellite link and the data are telemetered home over the same link. The Norrona's electronic officers load the AXIS system twice during each month's XBT section of 24 XBT drops between Iceland and the Shetlands. The AXIS was installed in the summer of 2013 and collected monthly XBT data between September 2013 and April 2016 when hardware problems halted data collection for the rest of 2016. The System was given a complete overhaul during the Norrona's December 2016 dry docking period and monthly data collection has resumed.

The Norrona's thermo-salinograph (TSG) has had a checkered history. When the ADCP was first installed in 2006, intake and exhaust valves were installed in the ship's engine cooling water intake plenum for a TSG. Sometime in the next year or so NIVA installed a TSG and PCO2 system on the ship as part of their Ferry-Box suite. The system was maintained until the

Norrona stopped serving Bergen at which point the system was allowed to deteriorate and ceased to function. We do not know what happened to the data collected during the first couple of years. We made several attempts to get the system revived including installing a new SBE21 TSG, a debubbler and a new GPS data feed in 2014. Finally, in January 2017 the software was updated by NIVA to handle the new GPS navigation message and TSG data collection has resumed.

Recirculation in the Faroe-Shetland Channel

In the two papers describing the results of the first four years of ADCP data collection across the Faroe-Shetland Channel, Rossby and Flagg, 2012 and Childers et al, 2014, the strength of the southerly flow along the Faroese shelf edge appeared large and was such that the net flow into the Norwegian Sea through the channel of warm Atlantic Water was less than expected. This led to the suggestion that perhaps some of this flow, referred to as the Southern Faroe Current (SFC), might turn westward at the southern end of the Faroe-Shetland Channel to circle around the Faroe Islands. There is clearly a tidally driven anti-cyclonic flow around the Faroes (Larsen et al., 2008) but whether this extended to the flow along the shelf break was unclear.

In an attempt to resolve fate of the SFC, Hansen et al (2017) reanalyzed the current and hydrographic data for the area of the southern Faroe-Shetland and Faroe Bank Channels. This detailed examination looked at, among other things, the current data from the southeast portion of the Faroese shelf which showed that there was very little of the Modified Atlantic Water of the SFC that went west through the Faroe Bank Channel. In addition, none of the drifters that passed north of the Faroes nor any of the few that entered the FSC, recirculated to the west around the Faroes. So if the SFC waters do not form part of anticyclonic flow around the Faroes, they must make a cyclonic turn in the FSC and become part of the Scottish slope current. This behavior must then show up in the current and XBT dataset from the Norrona's crossings of the FSC.

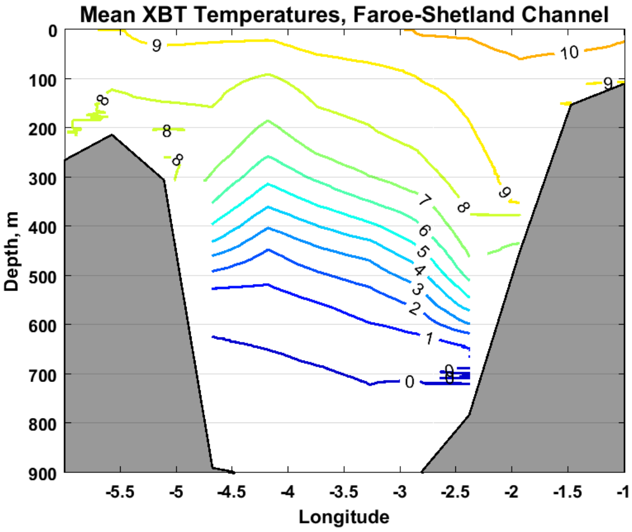


Figure 1. Mean temperature section from XBTs deployed between Oct 2013 - April 2016.

XBTs have been deployed monthly along the Iceland to Scotland track of the Norrona since fall 2013. From these data we can form mean temperature sections over the top ~900 meters, **Figure 1**. In the Faroe-Shetland Channel the mean section shows the southerly flow of Modified Atlantic Water in the Southern Faroe Current along the Faroese slope, as well as the expected flow of Atlantic water into the Norwegian Sea along the Scottish slope. The Eulerian mean temperature section tends to spread out both current systems such that the Scottish slope current appears to cover most of the channel while the highly variable SFC is narrow and muted. Another way to examine the temperature sections is to look at the time history of a single isotherm representing the separation between the warm Atlantic waters and the colder southward flowing overflow waters. The 5°C isotherm is often taken as a representative demarcation between these water masses and the vertical fluctuations of this isotherm surface is shown in **Figure 2**. This figures show that while on average the 5°C isotherm rises up from ~500m along the Scottish shelf to ~300m off the Faroes, there is considerably more variability in the isotherm depth along the western slope. Between 4°W and 4.5°W the 5°C isotherm's depth varies between about 500m to less than 200m during the 30 months of data shown while the time scale varies from 2-3 months to more than a year. An annual fit to the 5°C isotherm suggests that there is about a 50m depth variation which occurs along the Faroese slope about 3 months earlier than along the Scottish slope. However, this estimate is only based upon 30 months of data. Much more variability is associated with the shorter term variability with a typical time scale of 6 months. On top of these seasonal and shorter term variations is a decrease in the depth of the 5°C isotherm in 2015 by nearly 200 m compared to a year earlier.

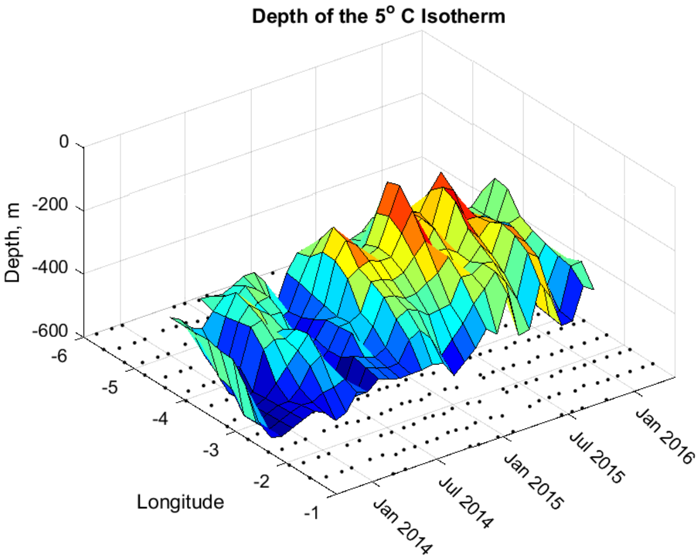


Figure 2. Hodograph of the depth of the 5°C isotherm in the FSC between Sept 2013 and April 2016.

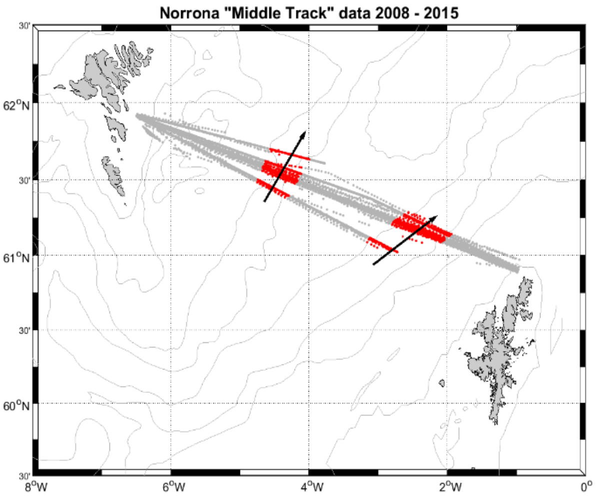


Figure 3. This plot shows the location of the ADCP data collected along the Norrona's middle track. The red points show the location of the data used in the cross-channel analysis discussed in the text.

The cross-channel variations in the isotherm depths suggests that there are significant variations in the along-channel velocities in the upper warm Atlantic waters. The question then arises as to whether the along-channel currents are coherent in some way across the channel, whether they represent an advective process with a significant time delay, or whether they result from some dynamic process that is felt all across the channel. This can be investigated using the ADCP data from the Norrona by examining the correlation between the along-channel flow on either side of the channel. The Norrona's track across the FSC has varied over the years, principally by going north or south of the Shetland Islands on its way to Denmark. The track north of the Shetlands, referred to and the "middle track", has been used most often and there are 170 sections which yield data on both sides of the FSC between the 500 and 1000 meter isobaths, **Figure 3**. After detiding the velocity data assuming a barotropic tide, the velocities between the 500 and 1000 meter isobaths were averaged over the upper 400 meters and rotated into the along isobaths components indicated in **Figure 3**. The correlation plot in **Figure 4** with most of the points in the upper-left quadrant clearly shows the oppositely directed flow on either side through the FSC. The correlation between the mean along-isobath velocities on either side of the channel was statistically significant at -0.25 with a P-value of 0.001. As defined by the principle components, the Type-2 regression line (green) is very near the one-to-one line indicating that a unit increase in flow to the south along the Faroese slope is very nearly equal to a similar increase to the north along the Scottish slope.

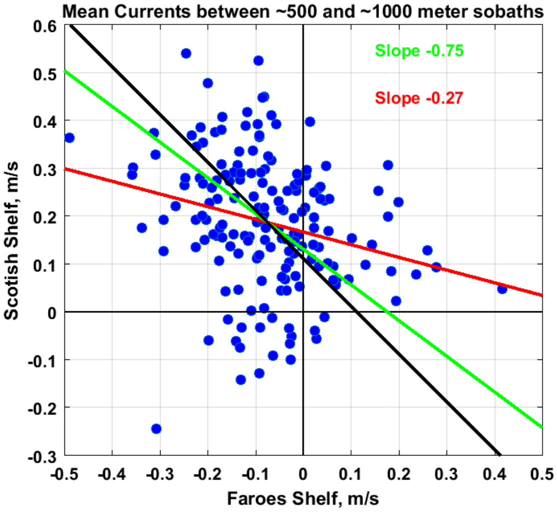


Figure 4. Scatter plot of the depth-averaged currents between the 500 and 1000 m isobaths on either side of the FSC.

Given that there seems to be a clear relationship between the flow on either side of the channel, how is that reflected in the cross-channel temperature, hence density, structure? **Figure 5** shows the mean velocities between the 500 and 1000m isobaths on either side of the channel, plotted against time. The figure shows that there was considerable variability in the currents but that there was a clear increase in along-channel flow on both sides of the channel in 2015 relative to 2014. This speed increase corresponds to the dramatic uplift of the 5°C isotherm shown in **Figure 2**. Another view is to contrast the cross-channel temperature structure at times when the along-channel velocities are minimal during August 2014 as compared to a time when the velocities are large in May 2015. The temperature sections for those times are shown in **Figure 6** where the characteristic doming

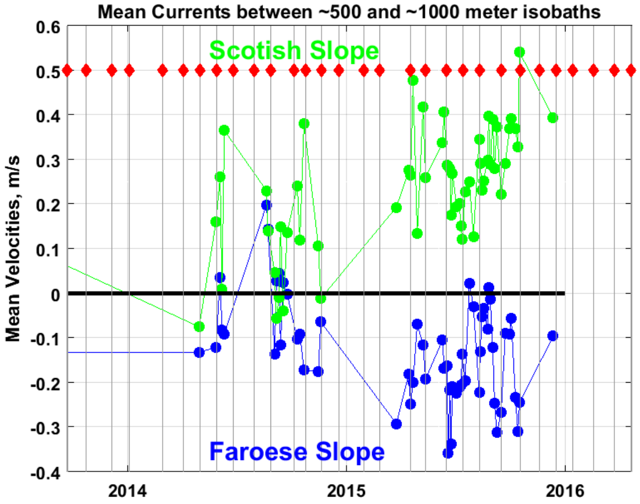
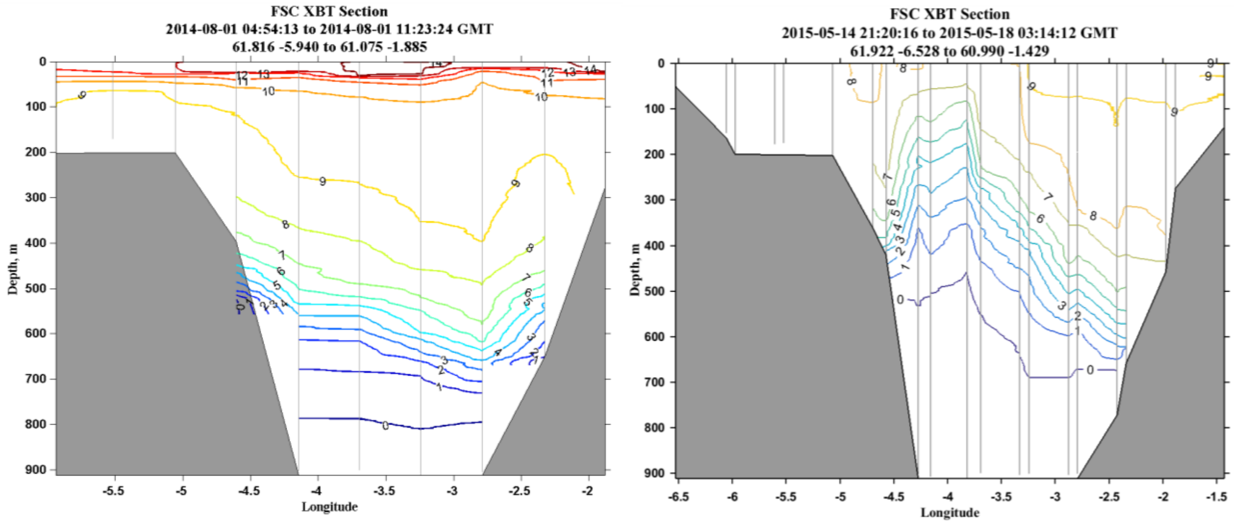


Figure 5. Depth-averaged velocities between 500 and 1000 m on either side of the FSC. Red diamonds show the times of XBT sections.

of the isotherms over the Faroese slope is completely absent in August 2014 and the 5°C isotherm is depressed to about 500m. Along the Scottish slope the isotherms show a reversal of the isotherm slope indicating a slow-down of the Faroe-Shetland Current. By contrast, the May 2015 shows very steep isotherms over the upper Faroese slope during which the 5°C isotherm rises from 400m to 100m and there is a strong southerly flow. On the Scottish side the Faroe-Shetland Current has sped up and extends more than half-way across the channel.



FSC XBT Section
2014-08-01 04:54:13 to 2014-08-01 11:23:24 GMT
61.816 -5.940 to 61.075 -1.885

FSC XBT Section
2015-05-14 21:20:16 to 2015-05-18 03:14:12 GMT
61.922 -6.528 to 60.990 -1.429

Figure 6. Cross-channel temperature sections from August 2014 when along-isobath flow was at a minimum, and May 2016 when the flow on either side of the FSC was near it maximum.

A11. Aspects of the circulation in the Faroe-Shetland Channel as inferred from altimetry

Léon Chafik, Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway

Aspects of the circulation in the Faroe-Shetland Channel (FSC), an important choke-point for the Atlantic meridional overturning circulation, are here discussed from an altimetric point of view. But first, we point out that the mean dynamic topography (MDT) in the North Atlantic and the Nordic Seas captures the large-scale flows (e.g. recirculation in the Faroe-Shetland Channel, both branches of the Norwegian Atlantic Current) and eddy/meandering structures (e.g. meanders of the North Atlantic Current east of the Grand Banks) to a far better extent than before, Fig. 1.

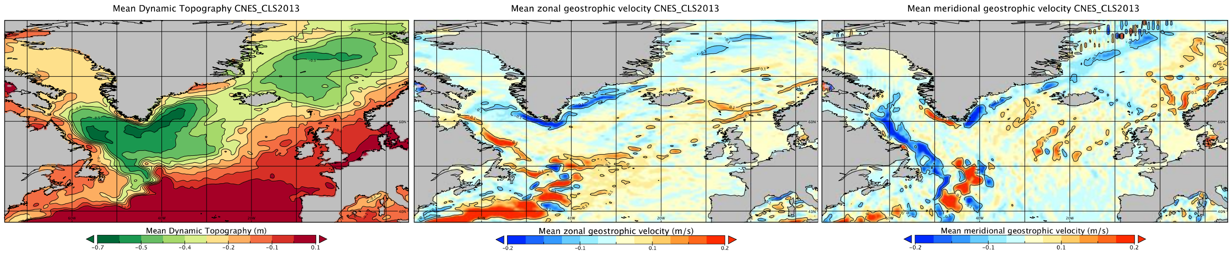


Figure 1: (left) Mean dynamic topography (CNES-CLS2013) and its associated (middle/right) mean zonal/meridional geostrophic velocities.

It is well-known that high eddy activity and eddy mean-flow interaction are complicating factor of the FSC circulation (Oey 1997, Sherwin et al. 1999, Sherwin et al. 2007, Chafik et al. 2012). For example, cold core eddies along the Faroe slope, most likely generated and originating at the Iceland-Faroe ridge (Hansen and Meincke, 1979) and the Faroe current (Hansen et al. 2015), have been found to be a dominant source of the variability (see Fig. 2). These eddies have the ability, apart from leading to a strong shoaling of the thermocline, to deflect the Shetland slope current into the middle of the channel (Sherwin et al. 1999, Chafik et al. 2012). This eddy-induced shift of the slope current core is also associated with large quantities of Atlantic Water shifting into the deeper parts of the channel (Chafik et al. 2012). This is one important reason for why the lateral extent of the barotropic current is at times not well defined on the Shetland shelf (Sherwin et al. 2007). Similarly, it is as yet unclear whether this current, on the Faroese slope, is mostly a response to these southward propagating cold core eddies or is it actually a persistent current?

Wind forcing variations is another factor that may contribute to this variability in the FSC. For example, the FSC circulation during strong (weak) westerly wind events is, as anticipated from the wind-driven barotropic flow along f/H contours, strongly (weakly) topographically steered. Chafik et al. (2012) reported that the perturbed flow structure during anomalously weak westerly wind events increases the overall eddy kinetic energy in the channel. Another aspect of these two flow regimes during periods of strong and weak westerly winds is their strong interaction with relationship to the shape and hence the strength of the Norwegian-Sea gyre, as indicated in Fig. 2. It shows geostrophic streamlines for high- and low- North Atlantic Oscillation (NAO) conditions, this to elucidate the role of the large-scale wind-field and the degree of topographic control exerted on the FSC flow. During high NAO events, the streamlines originating from the Norwegian Sea extend far southwards in the FSC before recirculating and joining those of Atlantic origin along the Shetland slope. During low NAO events, however, these streamlines retract northwards instead of constituting a part of the FSC recirculation.

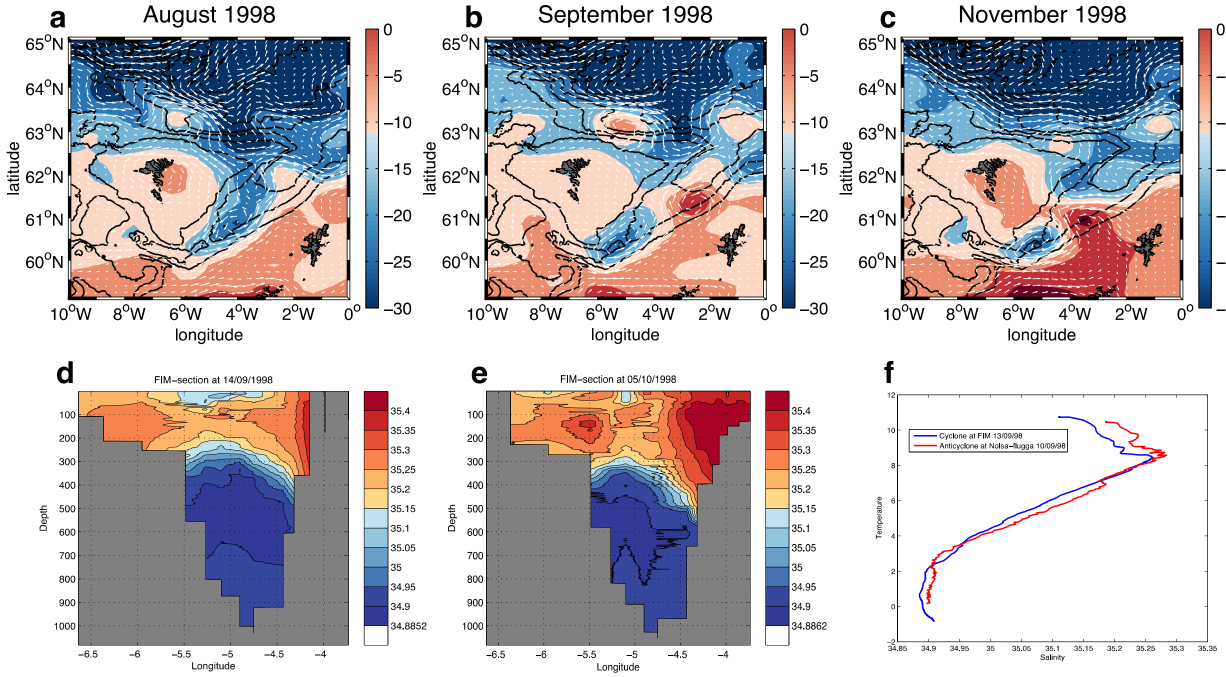


Figure 2: Evolution of the absolute dynamic topography (cm) and associated geostrophic velocities for (a) August, (b) September and (c) November 1998. Salinity at the FIM section (generously provided by B. Berx) during (d) September and (e) October. (f) Temperature-salinity diagram at stations in the middle of the channel across the FIM (across the anticyclonic eddy) and the Nolsoy-Flugga (across the cyclonic eddy) sections, respectively.

This NAO-associated behaviour is likely due to the strengthened/weakened wind-stress curl inducing an expansion/contraction of the Norwegian-Sea gyre with attendant consequences for the geostrophic streamlines. It may be concluded that these different flow patterns and associated mesoscale eddies and hydrographic signals in the FSC are a response to changes in the wind forcing, but could they also be a response to anomalous inflows to the Nordic Seas (e.g. Sandø et al. 2012)?

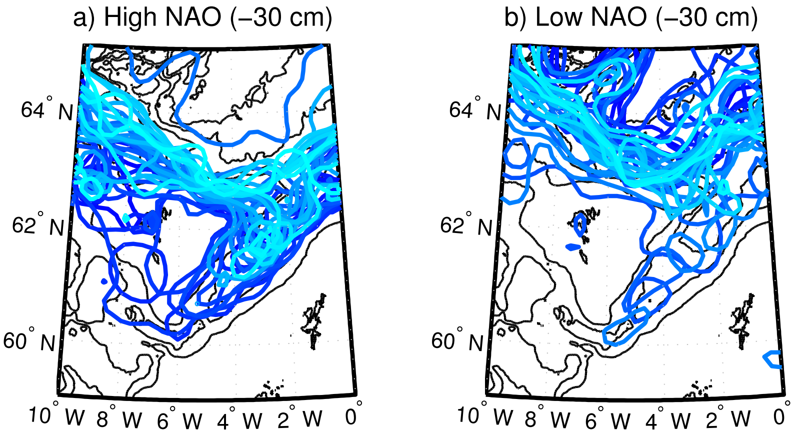


Figure 3: Absolute dynamic topography isolines originating from the Nordic Seas (-30 cm) during (a) high- and (b) low-NAO index events.

The warming of the Nordic Seas since 1996 has been attributed to enhanced advection of warm subtropical waters in response to the abrupt weakening of the subpolar gyre circulation (Hátún et al. 2003, Rhines et al. 2004, Skagseth and Mork 2010, Häkkinen et al. 2011). The invasion of subtropical waters has been linked to weakening of the wind stress curl and westward shift of the subpolar front, which, in turn, opens a northward route for these warm and saline waters. For example, the study by Skagseth and Mork (2010) also shows a clear positive ocean heat content trend in the Nordic Seas, with the Lofoten Basin and FSC (~6-8 W/m^2 between 1995 and 2010, see their Fig. 6) exhibiting the most obvious warming trends. Interestingly, we also note that the eddy kinetic energy in the channel has been increasing linearly over the past two decades, and this is most pronounced in the middle of the channel, which is similar to that of the ocean heat content (Skagseth and Mork 2010). Perhaps the increased invasion of warmer waters together with an increased frequency of the disruptive flow pattern described above have led to a higher eddy kinetic energy. This linkage involves different time scales, but it is assumed that during anomalously warm periods the negative NAO is usually also involved (Häkkinen et al. 2011). An in-depth investigation along these lines will thus be required to better understand this conspicuous increase of the eddy kinetic energy, and its implications for the hydrographic structure of the FSC.

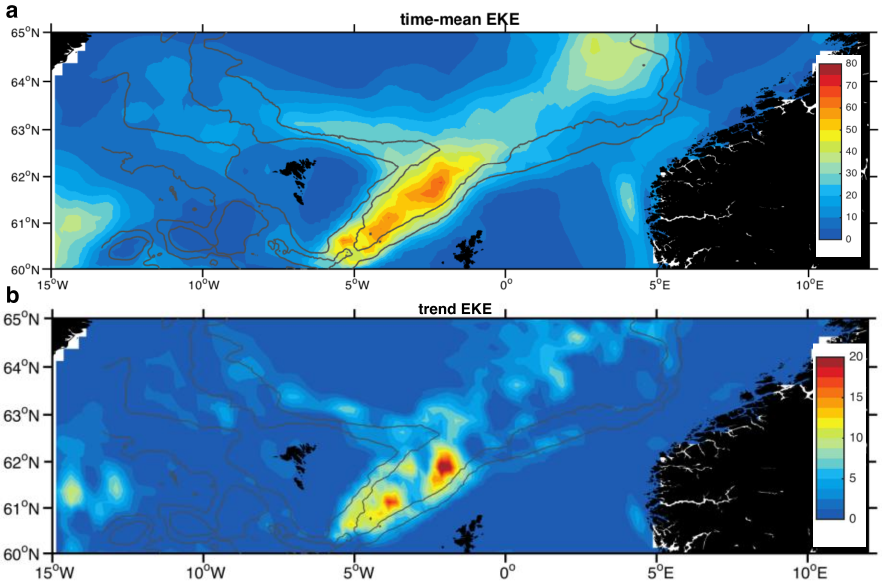


Figure 4: (a) Time-mean Eddy Kinetic Energy (EKE, cm^2/s^2) for the 1993-2015 period based on AVISO. (b) The linear trend (cm^2/s^2) of the 1993-2015 monthly EKE maps per decade. The solid lines indicate the 500 and 1000 m isobaths.

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A12. Modeling the exchanges across the Greenland-Scotland Ridge

Anne Britt Sandø, Institute of Marine Research and Bjerknes Centre for Climate Research

The exchange of waters between the North Atlantic Ocean and the Nordic Seas across the Greenland-Scotland ridge (GSR) is of major importance to the regional climate due to the 300 TW transport of heat into the Nordic and Arctic Seas and varies on many time scales. The water masses involved are the inflow of warm and saline Atlantic Water, and the export of light Polar Water at the surface and of dense Overflow Water at depth. Furthermore, the overflow of dense water from the Nordic Seas into the Atlantic Ocean across the GSR is the main source for North Atlantic deep water. The mechanisms behind the seasonal to inter-annual exchange variability have been a point of discussion for many years. Is the variability mainly due to the intensity of the southwesterly winds "pushing" Atlantic Water into the Nordic Seas, is it due to varying formation and export of dense and deep waters from the Nordic Seas, "pulling" the Atlantic Water northwards over the GSR, or is it a blend of both due to a common factor as for example the North Atlantic Oscillation (NAO)?

In the story presented here, the variable oceanic exchanges between the Nordic Seas and the Atlantic proper have been investigated using an isopycnic coordinate ocean model for the period 1948-2007. Observed and simulated time series of volume transports in the Denmark Strait (DS), between Iceland and the Faroe Islands, and in the Faroe-Shetland Channel (FSC) are used to evaluate the model, and the model captures much of the variability.

In addition, two other models with 10 km horizontal resolution have been evaluated with respect to variability and mean transports. Both models, the sigma-coordinate ROMS model and the z-coordinate NEMO model, show good estimates with respect to mean transports across the Greenland-Scotland Ridge, as well as in the Barents Sea Opening, but they have the same problems as MICOM to represent the variability, especially over the Iceland-Faroe Ridge.

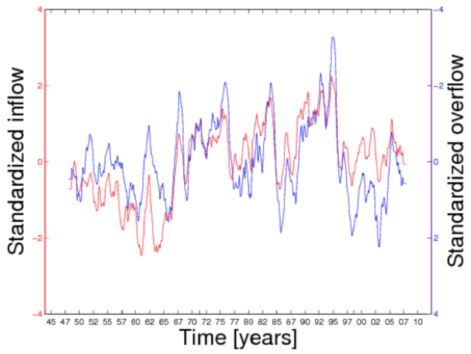
Back to the MICOM results. The inflow of Atlantic Water in the FSC, the outflow of light Polar Water in the DS, and of dense Overflow Water in both FSC and DS are all found to covary with an atmospheric pattern resembling the North Atlantic Oscillation. Increase in the FSC inflow is associated with decrease in the FSC overflow and increase in the DS overflow.

The exchanges' response to the atmospheric forcing is mainly of barotropic nature, but they are also influenced by baroclinic processes. The modelled antiphase between FSC inflow and overflow is connected to a vertical displacement of the isopycnal separating the two water masses in the channel and along the path of the Norwegian Atlantic Slope Current, consistent with hydraulic control of the FSC exchanges.

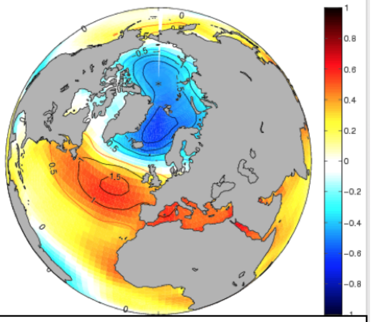
Another way that the atmospheric windstress may influence the overflow in the FSC, is by spinning up the cyclonic circulation in the Nordic Seas. The isopycnals will then be domed, i.e. be lifted in the center and lowered at the periphery and at the sill. In this way, variability in the wind stress on monthly time scales may influence the overflow.

Good correlation between modelled and **observed** Faroe-Shetland Channels (FSC) overflow

Simple mechanism behind?
Atmospheric forcing?

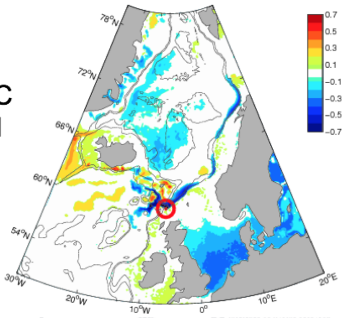


Correlation between FSC inflow and sea level pressure



1. FSC inflow increases due to stronger southwesterly winds and NAO.
2. Increased transports of Atlantic Water through the FSC tilt and depress the isopycnals below.
3. The resulting depth between the isopycnal separating inflow and overflow and the sill depth decreases, the overflow is impeded (hydraulic control).
4. In parallel to increased FSC inflow, there is a barotropic adjustment in terms of increased Denmark Strait outflow.

Correlation between FSC overflow and isopycnal depth



A13. ADCP in the North Sea

Håvard Vindenes, Institute of Marine Research, University of Bergen

For my talk, I presented briefly some results from extraction of tidal currents from ADCP data in the North Sea, which is what I've been working on recently for my Ph.D. project.

The ADCP data are recorded by hull mounted instruments on the M/V Nuka Arctica and the M/F Norröna. Both ships traverse the northern North Sea on a regular basis and have operated ADCPs for several years (Nuka Arctica 1999-2002, 2012-now, and Norröna 2008-now). This database is an especially valuable resource in an area where there is a lack of spatially and temporally extensive data sets of direct current observations.

The tides are of course important to be able to extract with some certainty of the accuracy for further analysis of the current observations. And while the circulation in the northern North Sea is not dominated by the tides to the same degree as in the southern North Sea, the tides are still relatively strong in some areas.

The extraction of the tidal currents from the observed current is naturally a bit more complicated when the data on which you apply harmonic analysis is variable both in space and time, but given a large data set like this the results look very promising. The method used for extracting the tidal currents relies on least squares fitting the current observations to basis functions that are specified at a set of knot points. This creates virtual time series at these knot points, to which the harmonic analysis can be applied.

The dominating tidal constituent, M2, describes approximately 40 % of the variability in the observed current in the study area. The strongest tidal currents, found in the Fair Isle Channel, are upwards of 70 cm/s. In other areas in the Norwegian Trench the currents are much weaker, some places not exceeding a few cm/s. The second most prominent constituent in the harmonic analysis is S2, which here is approximately one sixth as strong as the M2 tidal current overall.

Figures 1 and 2 show comparisons of the tidal ellipses calculated from the ADCP data and moored current meter data (at approximately 50 m depth), and ADCP data and model results, respectively.

Comparing the results with tidal currents obtained from moored instruments around the North Sea reveals a good agreement between the two. A regional tidal circulation model also gives very similar results in most areas. However, there are a few locations where the model severely underestimates the tidal currents when compared to those extracted from the ADCP data. This is especially true for the shelf areas just off the north-western coast of Denmark.

The next step in my project will be to study the current patterns and volume transport and their variation in the North Sea, and then use the results toward evaluating the circulation models that are utilized in the northern North Sea.

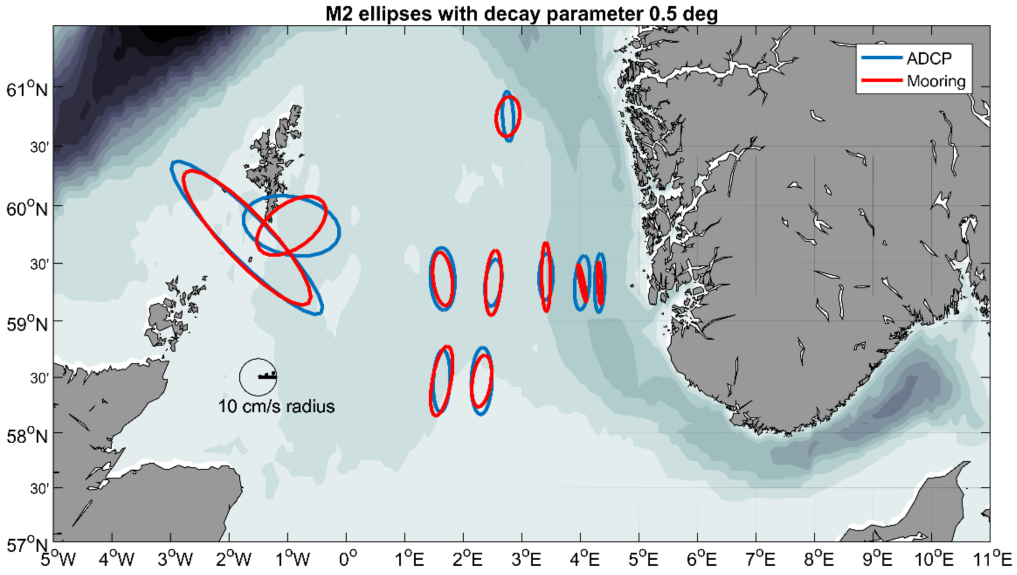


Figure 1: M2 tidal ellipses of tidal currents estimated from ADCP in blue, and moored current meters in red. The black circle is a 10 cm/s radius reference.

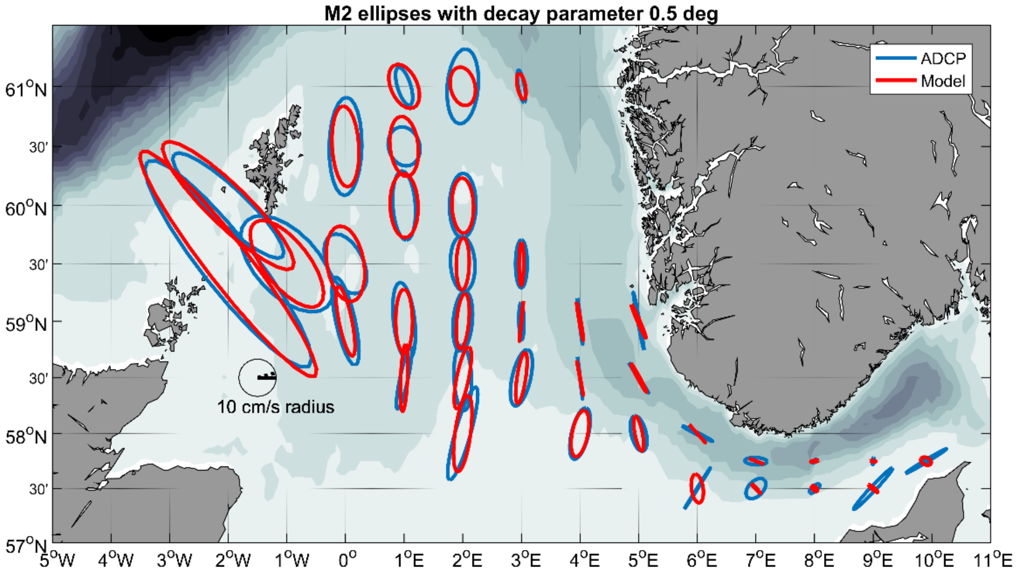


Figure 2: M2 tidal ellipse of ADCP in blue, and model in red.

A14. Faroe Bank Channel overflow

Karin Margretha H. Larsen, Faroe Marine Research Institute

The Greenland-Scotland Ridge forms the entrance to the Nordic Seas and here the northern limb of the AMOC takes place at a relatively shallow place. In the upper layer warm Atlantic water flows northward in three separate branches and in the lower layers the return flow in form of Overflow water crosses the ridge at its deepest channels and trenches. The deepest channel is the Faroe Bank Channel (FBC) with a sill depth of 840m, but it is only 10 km wide which makes the FBD overflow the second largest overflow branch, next to the Denmark Strait overflow.

Monitoring of the FBC overflow was initiated in 1995 and since then 1-2 RDI BroadBand Acoustic Doppler Current Profilers (ADCPs) have continuously been deployed at the sill only interrupted by annual turnarounds of the instruments. The most recent estimate of the overflow volume transport is 2.2 Sv with a slight, but not statistically significant positive trend (Figure 1a) (Hansen et al, 2016). Temperature measurements have also been done together with the current measurements. In the first years, temperature was measured using the ADCP temperature recorder, but in 2001 a Seabird Microcat was attached to the mooring yielding more accurate measurements. These data show that the temperature of the overflow water at the FBC sill has increased approximately 0.1 °C since the beginning of the 2000s (Figure 1b). The Seabird Microcat also measures salinity, but those measurements have shown be inaccurate and often with large jumps in the readings. Therefore CTD data from a standard section upstream of the sill have been used to estimate the salinity of the FBC overflow water. This analysis shows that the salinity of the overflow water has also increased, such that the density of the overflow water has remained stable during these two last decades (Hansen et al, 2016).

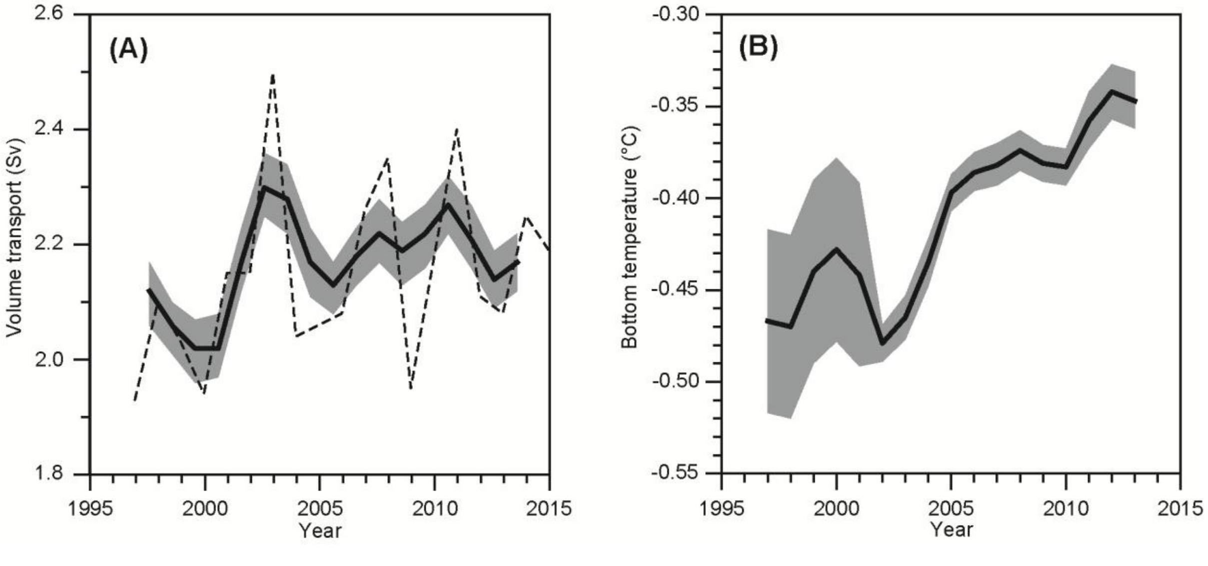


Figure 1. A) Long-term variations of kinematic overflow 1995–2015. Dashed line: Annually averaged transport excluding days 136–195; Continous line: 3-year-running mean transport with the shaded area representing +/- 1 standard error over each 3-year period. B) Bottom temperature at the FBC sill 1995–2015. Black line: 3-year-averaged temperature with the shaded area representing the uncertainty interval.

As the overflow water exits the FBC it descends down the slope while interacting with the surrounding Atlantic water. Several studies have been made of the fate of the FBC overflow plume and its transformation into Iceland Scotland Overflow Water (ISOW) (e.g. Mauritzen et al, 2005; Geyer et al, 2006). Generally, it is considered that the overflow plume entrains surrounding waters such that the volume transport is doubled (Mauritzen et al, 2005; Fogelqvist et al, 2003). More recently, however, it is suggested that considerable detrainment also takes place such that the contribution from the FBC overflow to the ISOW is not more than the volume transport at FBC sill level and maybe even less (Ullgren et al, 2016). Further investigations of the FBC plume is therefore requested, and in a pilot study, the Faroe Marine Research Institute has deployed two moorings at a location where a splitting of the plume possibly takes place. If this is the case, a southern and deeper branch of the plume might not be adequately observed in previous studies.

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Summary of a talk given at the Tórshavn Workshop 09.-10.01.2017

A15. The Iceland-Faroe-Ridge overflows

Detlef Quadfasel with contributions by Kerstin Jochumsen, Martin Moritz and Rolf Käse

University of Hamburg

The Iceland-Faroe-Ridge (IFR) is the about 400 km long central part of the Greenland-Scotland Ridge. It stretches from Iceland to the Faroe Islands, has a mean depth of about 400m and slopes from west to east (Fig. 1). Several deeper gaps cut through the sill crest. The exchange of water masses across the IFR contribute almost half (3.4 Sv) to the total inflow of Atlantic Water into the Nordic Seas *(Hansen and Østerhus, 2013),* but the ridge accommodates only about one sixth of the cold overflows into the North Atlantic (1 Sv) *(Meincke, 1983)*. There are two reasons for this: the earth's rotation and the bottom topography. They cause the bulk of the warm inflow to occur to the east of Iceland, but the largest overflows in the west, through Denmark Strait. A topographic curiosity is the very deep Faroe-Bank-Channel south of the Faroes that hosts a volume flux of about 2 Sv.

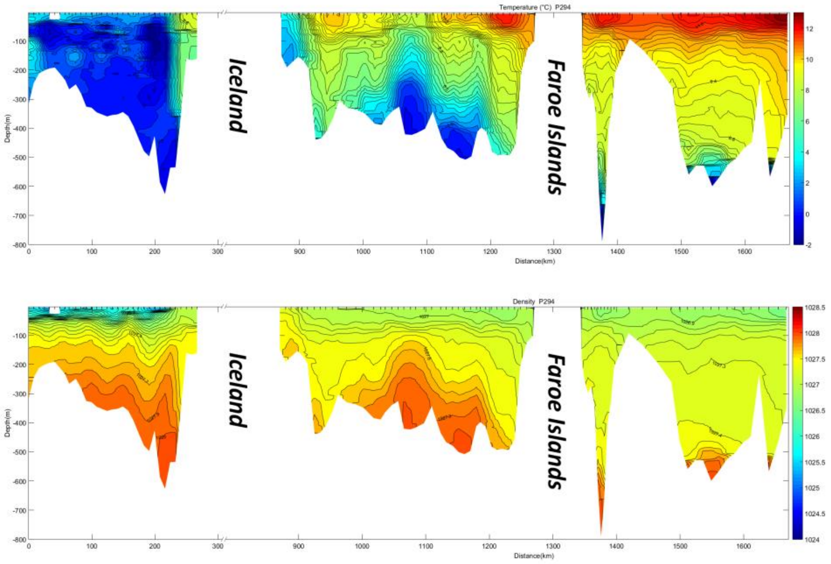

Figure 1: *Vertical distribution of potential temperature (top) and potential density (bottom) at a hydrographic section along the crest of the Greenland-Scotland Ridge. The west to east downward slope of the interface supports a geostrophic northward flow in the upper warm layer and a southward flux of cold water. Data were collected during RV POSEIDON cruise POS294 in September 2002.*

The existence of an overflow across the IFR has been known for more than a century *(Knudsen, 1898)*. The first transport calculations for the entire IFR overflow were carried out by *Dietrich (1956)*. His estimate of the overflow volume transport deduced from hydrographic data amounts to 5.8 Sv. However, he did not consider the geostrophic effect of turning the flow from across-slope to along-slope, which led to an estimate probably being almost an order of magnitude too large.

The first reasonable documented estimate for the total overflow volume transport across the Iceland-Faroe Ridge is provided by *Hermann (1967)* with data from the Overflow '60 expedition. In his study, a method for an equivalent thickness of the overflow layer is presented. Hydrographic cross sections over the ridge were run three times with only a few days in between. By tracing anomalies from the mean equivalent overflow thickness, the speeds of the overflow plumes were estimated. For most cases this compared well with direct current measurements recorded in the vicinity of the cross sections. By combining the velocities and equivalent thicknesses, an overflow volume transport estimate of 1.1 Sv was obtained for the IFR. This is close to that in the commonly cited literature source for an overflow transport of 1 Sv across the Iceland-Faroe Ridge, the review paper by *Meincke (1983)*. The author shows a scheme with an overflow of 0.5 Sv through the western valley close to Iceland and another 0.5 Sv distributed over the eastern part of the ridge. It is, however, not clear from the paper where these transport estimates originate from. Possibly the value is just the 1.1 Sv from Hermann (1967) rounded down to 1 Sv.

Several studies were dedicated to the intermittent character of the overflow through notches in the eastern part of the ridge. *Müller et al. (1974)* observed an overflow event through a gap of the IFR using temperature, salinity, light attenuation, and current measurements. The flow field indicated a perturbation leading to a spill-over of cold water through the channel. *Hansen and Meincke (1979)* used hydrographic data to demonstrate the existence of eddies and meanders over the Ridge. Those eddies can contribute to the transport of dense water across the ridge. As soon as they move cold and dense water southward over the crest, gravity will act on the water promoting its descent. Observations with bottom mounted ADCPs at the eastern part of the ridge also showed frequent occurrence of overflow water with a transition from stronger to weaker overflow in winter, but no transport estimate for the eastern part of the ridge is given *(Østerhus et al., 2008)*. At the western part of the IFR, *Perkins et al. (1994)* observed an overflow event that had a pulsating character.

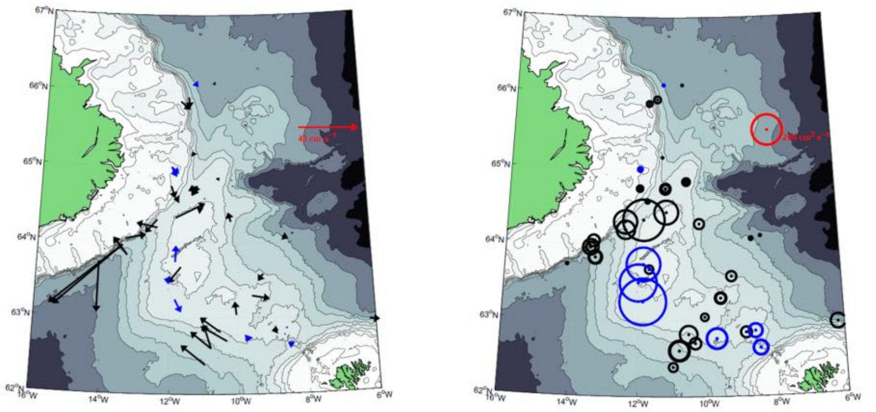

***Figure 2:** Mean currents (left) and current circles indicating the amplitude of synoptic scale variability (right) over the IFR, based on historical moored current meter records in the near bottom layer (Vogt, 2007). Black symbols indicate records longer than 250 days.*

As part of his diploma thesis Martin Vogt analysed historical moored current meter records from the IFR that were collected since the 1970s (Figure 2). Current speeds in the cold bottom layer are generally weaker than 0.1 m/s. Exemptions are found in the trench downstream of the western valley at the continental slope of Iceland and well south of the ridge's crest. RMS current speeds associated with synoptic scale eddies are about 0.1 – 0.2 m/s, being largest in the western part of the IFR *(Vogt, 2007)*.

Despite the intermittency of overflows at single locations over the western part of the ridge, the flow in the deep western boundary currents along the Icelandic slope is remarkably stable with persistent speeds of 0.5 m/s in the bottom layer *(Perkins et al., 1998)*. The accumulated volume transport calculated from current meter records collected about 100 km south of the ridge crest and two hydrographic sections at the Icelandic slope amounts to 0.7 Sv of pure overflow water. Data from a moored ADCP at about the same location, from 2005-2007, support these findings of overflow through the western valley *(Voet, 2010; Olsen et al., 2016)*. Bottom temperatures measured at the mooring varied between 2° and 5° C (mean 4° C) indicating an about 1:1 mixture of the original overflow water with the overlying warm Atlantic Water. *Voet's (2010)* transport estimates for this western valley range between 0.2 and 0.4 Sv using the current data and between 0.2 and 0.5 Sv using hydrography and assuming maximum hydraulically controlled flow. *Beard et al's. (2013)* estimates based of sea glider observations range between 0.07 and 1.17 Sv with a mean of 0.6 Sv which corresponds to about 0.3 Sv of undiluted overflow water. Applying hydraulic control to the whole of the IFR with its four deeper trenches including the western valley *Voet (2010)* estimated a total overflow of 0.5 – 1.2 Sv of northern water with temperatures below 0° C.

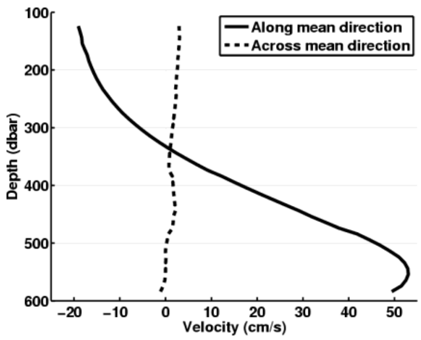

***Figure 3:** Mean current profile from a bottom mounted ADCP mooring in the western valley about 100 km downstream from the sill (from Voet, 2010)*

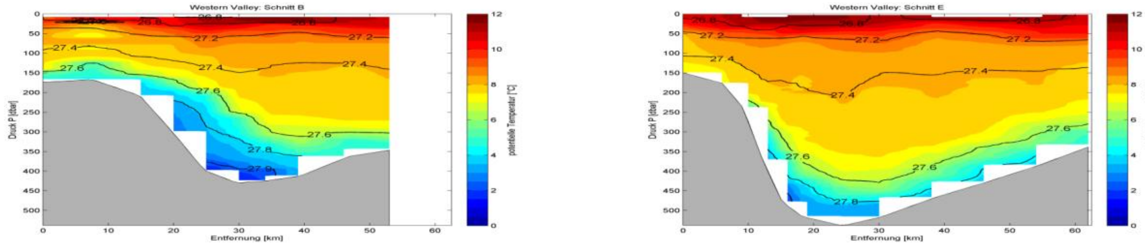

Figure 4: *Potential temperature/density anomaly sections across the western valley at the sill (left) and 60 km downstream (right).*

The temperature/density anomaly section over the sill of the western valley show an about 100 m thick layer of cold and dense (>27.8 kg/m^3) overflow water with a width of 25 km, 2-3 times the local deformation radius (Figure 4). It fills the deep part of the valley and hugs on the continental slope of Iceland. Just 60 km further to the south the thickness of the bottom layer is reduced to about half but the width of the layer has doubled. Here dense water is also found at the eastern flank of the valley. As already pointed out by *Beaird et al. (2013)* this eastern part may reflect a recirculation of overflow waters from the more eastern part of the IFR that initially flows westward and then recirculates in the southern part of the western valley.

Outlook: In summer 2016 an ADCP mooring was deployed on the sill of the western valley, along with two bottom mounted temperature recorders east and west of it (Karin M. Larsen) and two Inverted Echosounders to the north and south. During the next couple of years hydrographic and current profiling work will be done annually, to study the fluxes and the mixing of water masses along the western valley (Kerstin Jochumsen).

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A16. Numerical and laboratory models of dense water overflows over the Scotland-Iceland ridge: Pathways, Ekman transports, mixing and entrainment

by Jarle Berntsen, University of Bergen, Norway

1. Background

The presentation at the workshop was based on a proposal addressing numerical modeling of overflows in general, and the Scotland-Iceland ridge overflows were selected as the test case, see Fig. 1. The long term overall goal is to establish sub-models for dense water overflows in climate models, and there are many specific goals for the overflows between Scotland and Iceland that we want to address. To perform the investigations a team consisting of numerical modelers, experts in fluid mechanics with experience with laboratory work and senior scientists that know the targeted overflow areas and observational systems was built. The team was from Norway Jarle Berntsen and Elin Darelius, University of Bergen, Vidar Lien, Paul Budgell and Anne Britt Sandø from the Institute of Marine Research and Svein Østerhus, UNI Research, from UK Peter A. Davies, University of Dundee, Alan Cuthbertson, Heriot Watt University and Magda Carr, University of St Andrews. From the Faroe Marine Research Institute, Faroe Islands, Bogi Hansen and Karin Margretha Larsen joined the team and from Sweden Anna Wåhlin, University of Gothenburg.

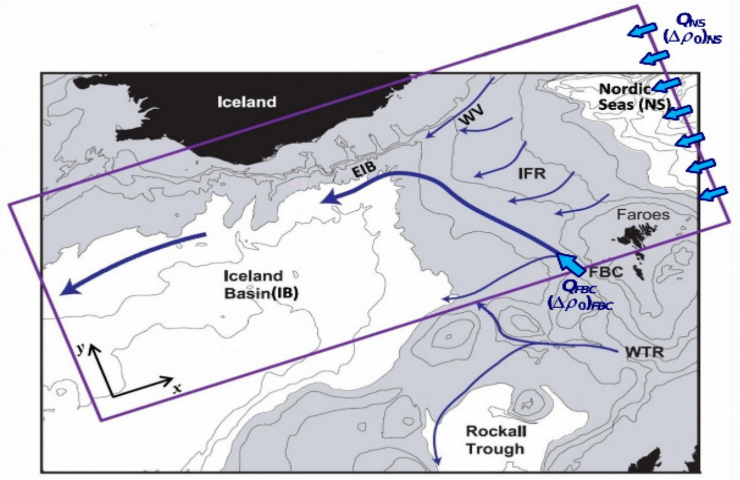

Figure 1: Pathways of overflow water from the Nordic Seas into the eastern North Atlantic. Plan view showing the extent and horizontal coordinate system (x, y) of the rectangular regional model to be used to investigate the pathways of overflow water of volume flux Q and density excess $\Delta\rho_0$ into the Iceland basin (IB) from the Nordic Seas (NS) via (i) the Faroe Bank Channel (FBC) and (ii) the Iceland Faroe Ridge (IFR) after Hansen and Østerhus [2000]. (In the figure EIB, WV and WTR represent the East Iceland Shelf Boundary, the Western Valley and the Wyville Thompson Ridge respectively)

2. The overflows over the Scotland-Iceland ridge

There is a substantial literature on the ocean fluxes between the Nordic seas and the North Atlantic, see for instance Dickson et al. [2008]. The FBC overflow is constrained to flow through a narrow deep channel and is easily monitored with relatively small efforts. We therefore know its average properties and volume transport with high accuracy and know its variations through the last two decades (Hansen et al. [2016]). The overflow across the Iceland-Faroe Ridge, in contrast, occurs widely distributed and highly variable across the length of the Ridge (Østerhus et al. [2008], Beaird et al. [2013]). The average volume transport of the Iceland-Faroe Ridge overflow is therefore not reliably known within a factor of 2. When it comes to estimating the effects of these two overflows on the AMOC and the climate systems, the situation is different, mainly because of our very limited understanding of the entrainment/detrainment processes, see Mauritzen et al. [2005], Hansen and Østerhus [2007], Østerhus et al. [2008], Darelius et al. [2011], Beaird et al. [2012, 2013], Ullgren et al. [2016], Hansen et al. [2016].

There is a substantial supply of dense water over the Iceland-Faroe Ridge. The magnitude of this overflow is around 1 Sv. In the project description for the Western Valley Overflow project, it is stated that goals are ”to 1) measure the overflow of cold water from the Arctic into the rest of the World Ocean through the Western valley of the Iceland-Faroe Ridge, to 2) allow the effects of this flow to be adequately simulated in climate model projections of the thermohaline circulation and the heat transport towards the Arctic, and to 3) design a low-cost monitoring system for this flow.” We want to contribute to the WOV project by using numerical and laboratory models.

Using a combination of numerical models, a laboratory model and analysis of oceanographic data we want to investigate the pathways of the overflow over the Iceland-Faroe ridge, the merging of the FBC and IFR overflows, the consequences of this merging for the downstream overflow pathways and dynamics, the role played by the East Iceland shelf (EIS) boundary in controlling the outflow dynamics within the Iceland Basin (IB), and mixing, entrainment, and detrainment, in these overflows with a particular focus on hot spots.

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A17: Gliders on the Iceland Faroe Ridge: Structure of the IFR polar front: geostrophic velocity, overflow water on the Atlantic flank

Nick Beaird (WHOI), Peter Rhines (UW)

Between 2006 and 2009 continuous deployments of autonomous gliders made approximately 17,000 hydrographic profiles in the vicinity of the ridge. These data were used to investigate the structure, transport and modification of the dense overflows from both the Faroe Bank Channel and the Iceland-Faroe Ridge (IFR) as they flow along the Atlantic side of the IFR.

Simple along-stream divergence of mean geostrophic transport of dense water along the IFR (including modeled Ekman effects) suggest 0.8 Sv of overflow across the IFR

28 glider sections at the 'Western Valley' observed overflow there, showing a mean of 0.5 Sv, with a min of 0.05 Sv and a max of 2.13 Sv. Glider inferred dissipation (mixing & modification) is also elevated in this WV overflow

Averaging lots of glider dives in the FBC region show the bifurcation of the overflow plume around the topographic bump near 10 W

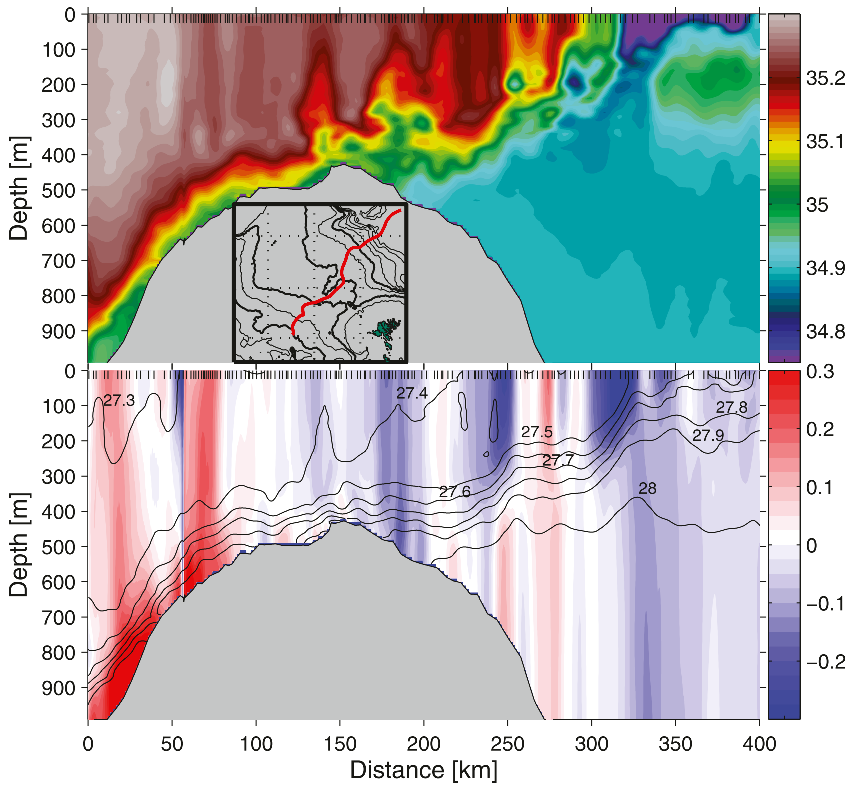


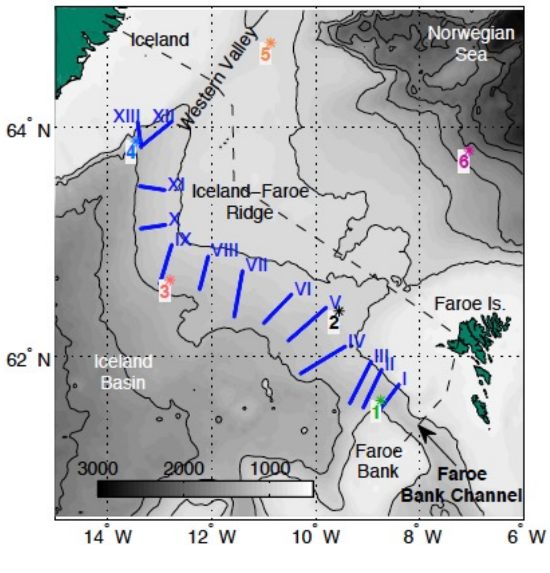
FIG. 2. (top) Salinity contours on a section normal to the IFR occupied by an SG on 3–23 Dec 2007. Dive and climb positions are shown as black vertical tick marks along the upper x axis. Location of the track is shown in the inset map. (bottom) Absolute geostrophic velocity [cross-section component, color contours (m s^{-1})] and potential density [black contours (kg m^{-3})]. Positive velocities are toward the northwest.

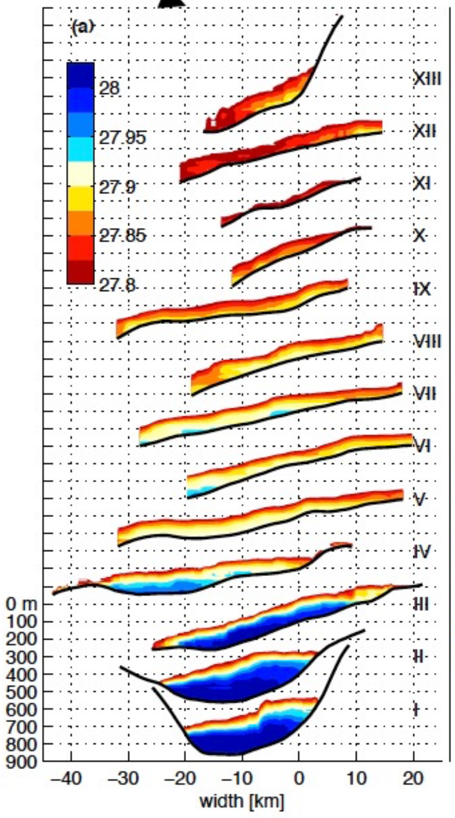
Overflows along the IFR

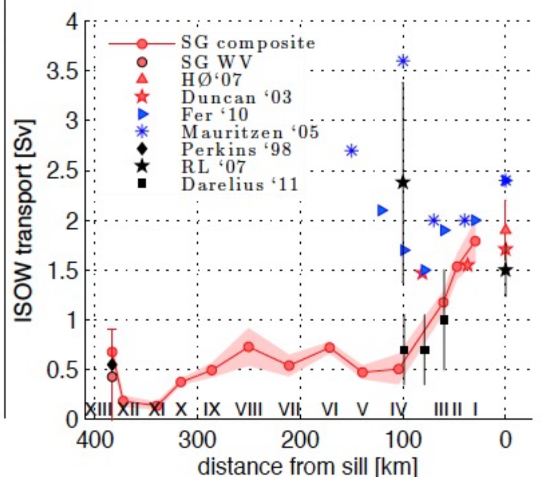
Using all the glider data, we made **mean cross-slope sections of density and geostrophic velocity** to look at the downstream changes in dense transport

mean overflow density sections

Residual along slope transport, including Ekman contribution, and the Iceland shelf overflow suggest 0.8 Sv of IFR overflow







Deep mixing in the overflows: FSC and IFR mixing inferred from glider vertical velocity with comparisons to microstructure profiles

A dimensional scaling for turbulent kinetic energy dissipation that utilizes glider vertical velocity measurements shows good agreement with traditional shear-based microstructure observations in the Faroe Bank Channel

Mixing inferred from the glider vertical velocity shows independent hot spots at the FBC primary sill and at the western FBC channel mouth (secondary sill), and again at the Iceland-end of the IFR in the 'Western Valley' Overflow

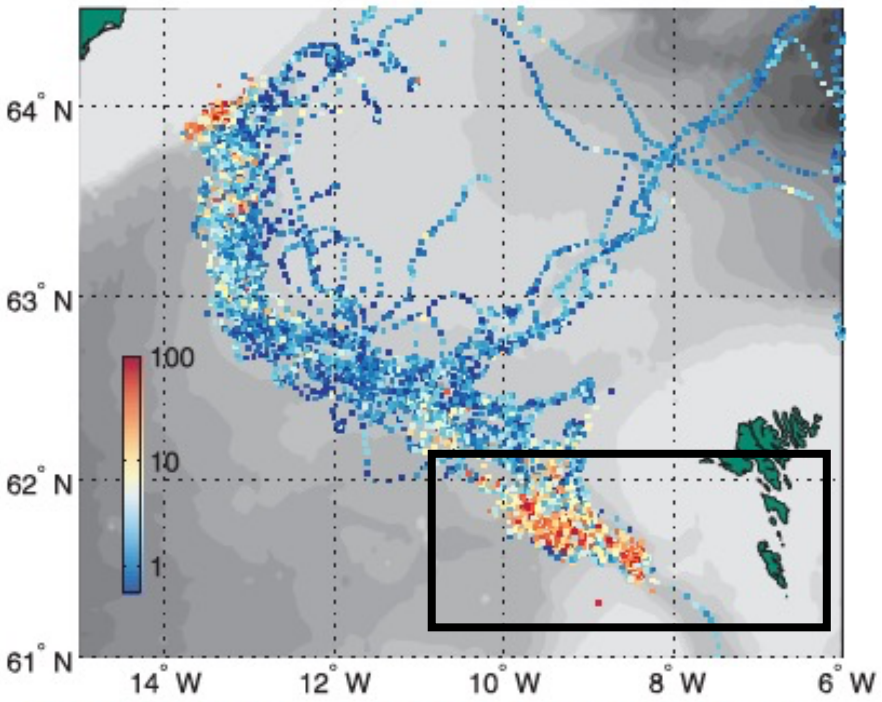


FIG. 10. Vertically integrated dissipation rates over the plume thickness, $\rho_0 \int_0^{H_p} \varepsilon\, dz$ (mW m^{-2}), from all Seaglider data.

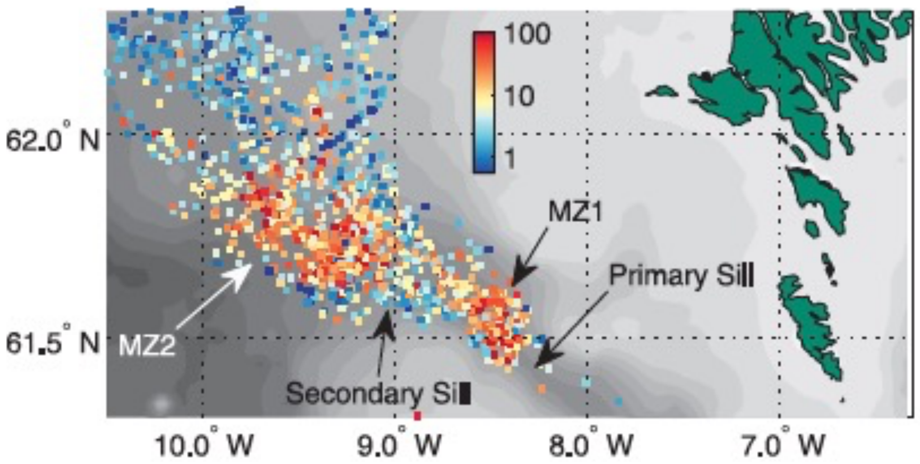


FIG. 11. Vertically integrated dissipation rates over the plume thickness, $\rho_0 \int_0^{H_p} \varepsilon\, dz$ (mW m^{-2}), in the FBC. MZ1 and MZ2 indicate the general region of the two enhanced mixing locations described in the text.

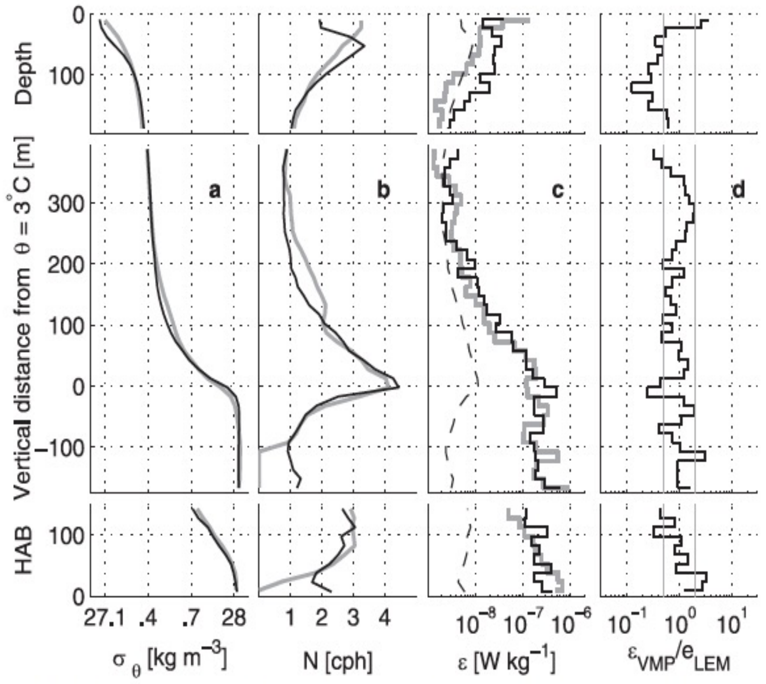


FIG. 6. Survey-averaged profiles of (a) potential density anomaly σ_θ, (b) buoyancy frequency N, (c) dissipation of TKE ε, and (d) ratio of VMP to sg005 dissipation estimates. VMP profiles are plotted in gray; Seaglider (sg005) profiles in black. Profiles are averaged with respect to (top) depth, (middle) distance from the 3°C isotherm, and (bottom) height above bottom in 15-m bins. Average noise level (i.e., lowest detection level) for the LEM [Eq. (7)] is plotted as a dashed black line in (c). Light gray lines in (d) show factor of 2 bounds on the estimate ratio.

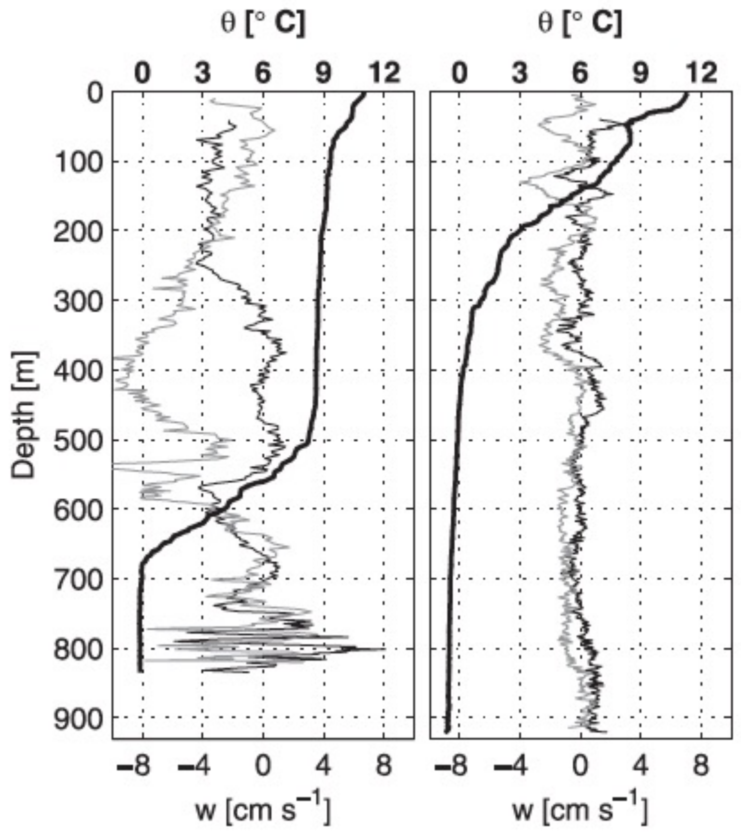


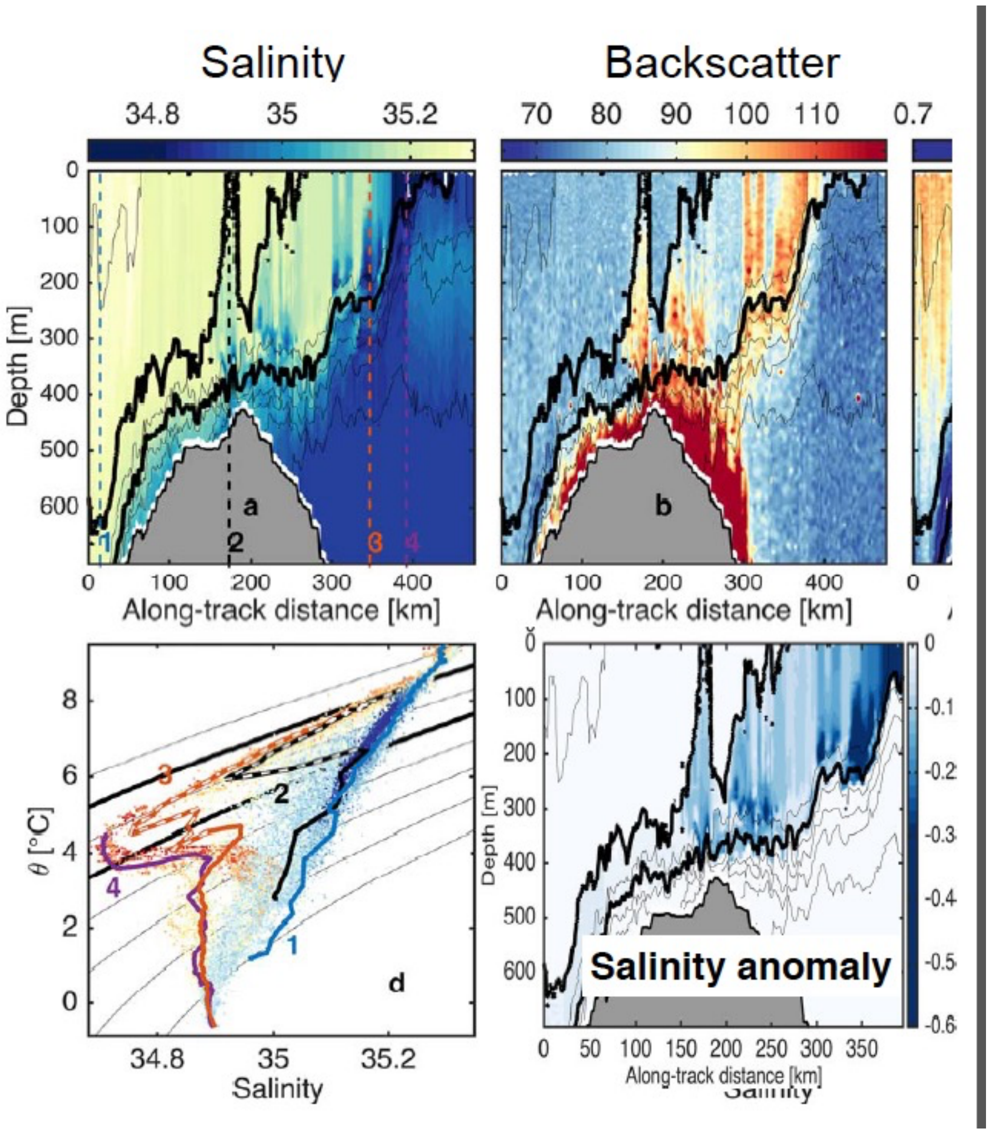
FIG. 3. Velocity profiles from the dives (black) and climbs (gray) as well as potential temperature (thick black, refer to top axis) from two Seaglider dives: (left) a dive in the FBC into the overflow plume and (right) a dive in a calm, deep, region north of the IFR in the open Norwegian Sea.

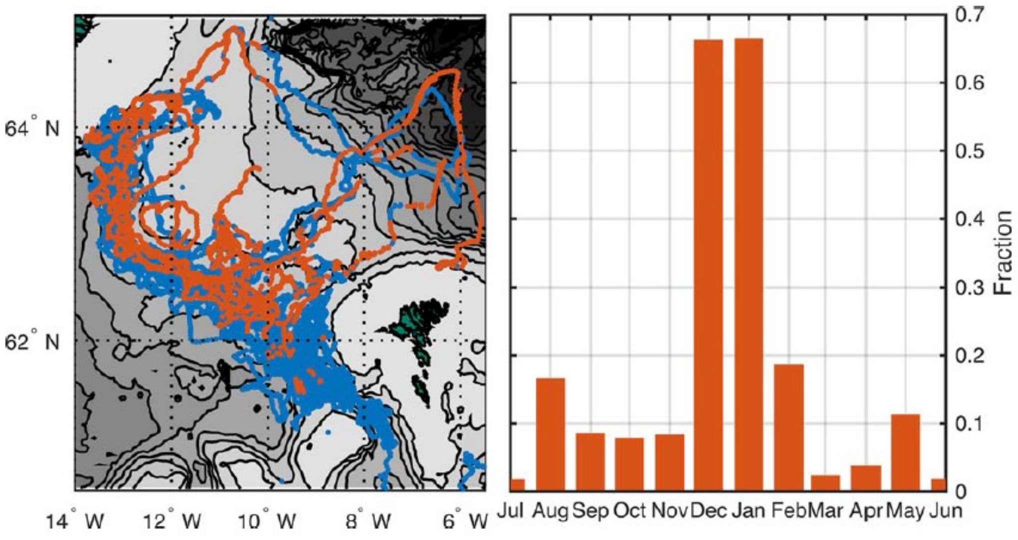
Structure of the IFR polar front: mixing and intrusions during winter

Salinity anomaly on isopycanals shows fresh water subducting from the surface of the IFF

Low salinity features are high in backscatter: zooplankton? phytoplankton?

Subducting low salinity features are only seen in the beginning of winter (Nov-Jan) — contemporaneous with mixed layer deepening





(left) geographic distribution of profiles with identified LSFW thermohaline intrusions in the potential density anomaly range 27:4 to 27:65. Each dot represents a glider profile where red points show profiles with intrusions, blue profiles without. (right) Seasonal distribution of the fraction of profiles with intrusions.

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