The Danish
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# DMI Report 21-20 AMOC and Arctic-Atlantic linkages

## Final scientific report of the 2020 National Centre for Climate Research Work Package 1.2.1, AMOC

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# Content

# 1 Abstract

Scientific advances has been made within three areas 1) Assessing the likely climatic presence of a flow of cold, dense water towards the North Atlantic in the complex region between Iceland and the Faroe Islands. Dense overflow water at the Iceland-Faroe Ridge contributes with unknown strength to feed the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). Results based on new as well as past data are corroborating the existence of a transport but require further analysis and quantification. Also, a new ocean model tool is developed that allows simulating better the complex circulation in the region and interactions of ocean currents with the complex bathymetry. This includes a nested high resolution model zoom to support the analysis and interpretation of new data to be recovered in 2021from already deployed ocean moorings; 2) A hitherto overlooked freshwater pathway has been identified as contributing to the low upper ocean salinities that has emerged in the eastern part of the subpolar North Atlantic since 2014/15; 3) To substantiate a working hypothesis that recent accumulation of fresh water in the Arctic helps to explain the observed stability of the AMOC and its regional components. A reduction in the AMOC is expected with ongoing global warming, but the observed strength of the AMOC and in particular its regional components in the eastern North Atlantic show a remarkably stability on decadal time-scales.

# 2 Resumé

Resultater fra arbejdspakken kan grupperes indenfor tre temaer 1) Returstrømning af koldt dybvand fra Arktis. Her er det sandsynliggjort at der eksisterer en hidtil ikke opmålt returstrømning af koldt dybvand fra Arktis mellem Island og Færøerne. En ny målekampagne er blevet planlagt og igangsat for at måle styrken af strømningen som bidrager til den dybe del af den atlantiske storskala-cirkulation (AMOC). Et nyt modelværktøj er blevet udviklet til bedre at simulere cirkulationen over Island-Færø Ryggen og interaktionen mellem den komplekse bundtopografi og havstrømme. Dette inkluderer en indlejret højopløst zoom af området som vil understøtte analysen af nye data der efter planen indhentes 2021 fra oceanografiske forankringer. 2) Unormalt lave saltholdigheder kan kobles til ændrede havstrømme omkring Island.
Vi har givet en ny forklaring på de ekstremt lave saltholdigheder der er observeret i den østlige del af det subpolare havområde i årene efter de unormalt kolde forhold i 2014/15; 3) Ferskvand i Arktis holder måske hånden under Golfstrømmen. Arktis ser vi at ferskvand fra floder og smeltet is er holdt delvist tilbage af de fremherskende vindsystemer over et årti. I andre vejrsystemer strømmer ferskvandet med de sydgående strømme til Nordatlanten. Niveauet er så højt at en pludselig udstrømning vil kunne påvirke vejr og klima i Nordatlanten. Vores foreløbige resultater antyder en anden vigtig vinkel, netop at Arktis herved kan være med til at holde hånden under styrken af AMOC og den nordatlantiske forlængelse af Golfstrømmen.

# 3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

Here we report on work specific to WP NCKF-AMOC 1.2.1 which is a project within NCKF carried out throughout 2020 and with consolidating activities planned for 2021.

The objective of the project is to achieve a better understanding of the relationship between components of the AMOC and climate variability in the Arctic and subpolar ocean regions with linkages to European weather and climate.

New knowledge on the outflow of deep water from the Arctic is central in order to verify and develop climate models and assesses the present uncertainties in climate sensitivity and tipping elements in the climate system related to the AMOC. Even today, we still only have indirect estimates of the strength of arguably climatic important components of cold deep water exchange between Iceland and the Faroe Islands. Here, direct, long-term observations are too sparse to make robust estimates. This is mainly due to the fact that the region of the Iceland Faroe Ridge is heavily fished preventing instrumentation by classical oceanographic moorings and, that the bathymetry is complex and bottom currents challenging to adequately measure. Moreover, there is neither good agreement across individual ocean model assessments or in between models and the sparse observations (Olsen et al. 2016). Our research is targeting this flow with numerical ocean modelling and observations.

Recent changes in the North Atlantic are amongst the most significant in the historic records and have left a number of unresolved scientific questions by challenging the established scientific understanding (e.g. Lozier et al 2019). Also, these changes and impacts have not been well predicted or fully captured by decadal prediction systems or subsequent hindcast experiments (e.g. performed as part of the Blue-Action project, www.blue-action.eu). Amongst the most significant changes is the extraordinarily cold upper ocean conditions that developed in 2014/15 in the western subpolar North Atlantic linked to cold air outbreaks from the North American continent. These cold conditions have been followed by unusually low salinities in the eastern subpolar north Atlantic (Holiday et al. 2020). Here we also see indications of a change in the interplay between warm and saline waters from the subtropics and colder fresher waters of the subpolar regions.

Freshwater is a critical component of the ocean climate system and interacts with both upper and deep branches of the AMOC at different time scales (e.g. Dickson et al. 1988). Connected to the arctic amplification of global warming, retreating snow cover and sea ice, large changes are already evident in the polar freshwater budget (Rabe et al. 2014). If connected to climate change, these changes can be expected to accelerate in the future and variability to increase. Here we examine the link between trends in freshwater content in the Arctic Ocean, the AMOC and its regional components. Freshwater affects a number of processes in the subpolar ocean, but is also seen returning with the North Atlantic current to the arctic regions, where it can potentially affect deep-water formation. The AMOC is expected to weaken with global warming, an effect that has not yet been seen strongly in measurements. A detailed understanding of the natural climate variability in the North Atlantic will also help us establish advanced criteria for selecting the most credible climate models, climate change scenarios and predictions of decadal climate variability.

# 4 Linking AMOC to variability in Arctic Ocean freshwater storage

We use data from the EC-Earth3 global climate model (Döscher et al., submitted) participating in CMIP6/AR6. More specifically, we analyse a 1000 year long preindustrial control simulation with the EC-Earth3, in which all external forcings are kept constant at preindustrial levels throughout the simulation according to the CMIP6 protocol. The strength of the AMOC is defined for each month as the maximum at 30° N of the zonal average meridional overturning stream function in the Atlantic Ocean sector of the global model. The annual mean of this index is used for further analysis. The total fresh water content is calculated for the upper Arctic Ocean relative to a reference ocean salinity of 34.8 for the liquid fraction. Sea-ice and snow on ice is considered pure freshwater.

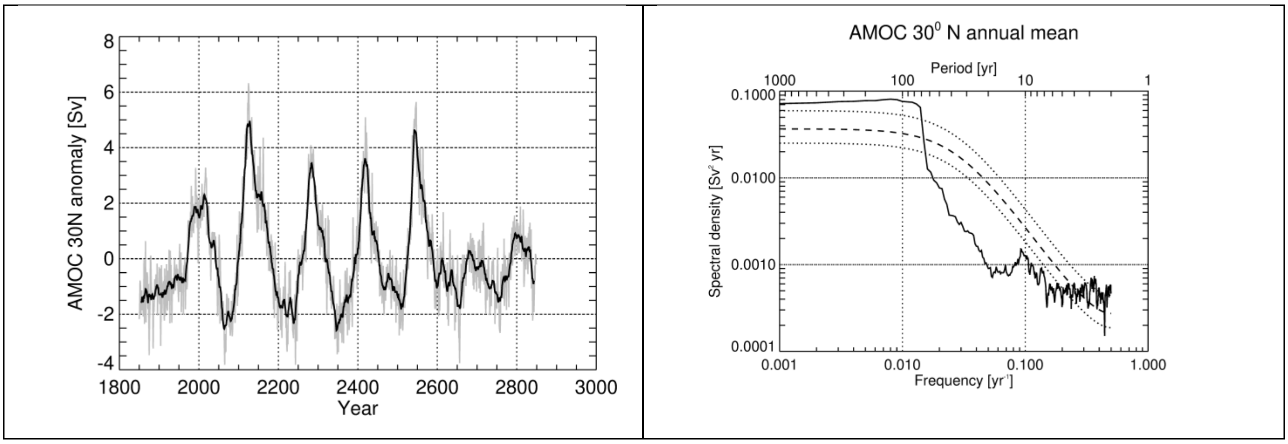

Figure 1 Annual mean anomalies of AMOC strength at 30° N (left). Grey curve are annual values, black curve is 11-year running mean. Associated power density spectrum (right). The dashed curve is a fitted AR(1)-spectrum while dotted lines delimit its 90 % confidence interval of the AR process.

Time series of the AMOC strength is shown in Figure 1 together with its spectrum. Predominant, recurring positive/negative anomalies are seen. This is consistent with the spectrum not coinciding with the fitted AR(1)-spectrum but with excess power at centennial time scales and less power at decadal/multidecadal time scales.

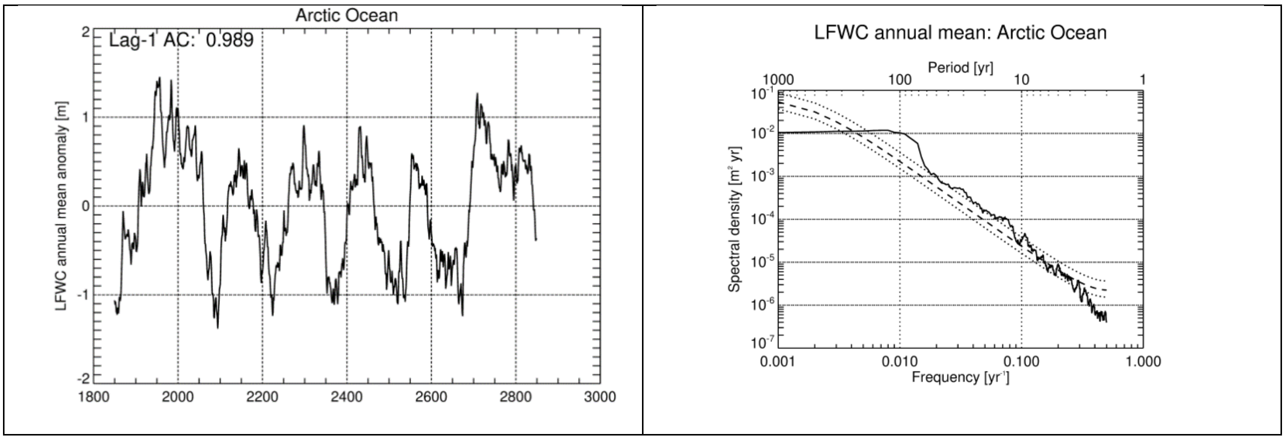

Figure 2. As for Figure 1, but for the Arctic Ocean total freshwater content.

Time series of the Arctic Ocean liquid freshwater content and the associated spectrum is shown in Figure 2. Also here there are large recurring anomalies with a centennial time scale, which is confirmed in the spectrum, where excess power relative to the AR(1)-fit is seen. Note also the lag-1 autocorrelation which is close to unity, meaning that the series may better be described as a random walk; this issue requires a more in-depth analysis.

The spatial distribution of liquid freshwater variability is illustrated in Figure 3.

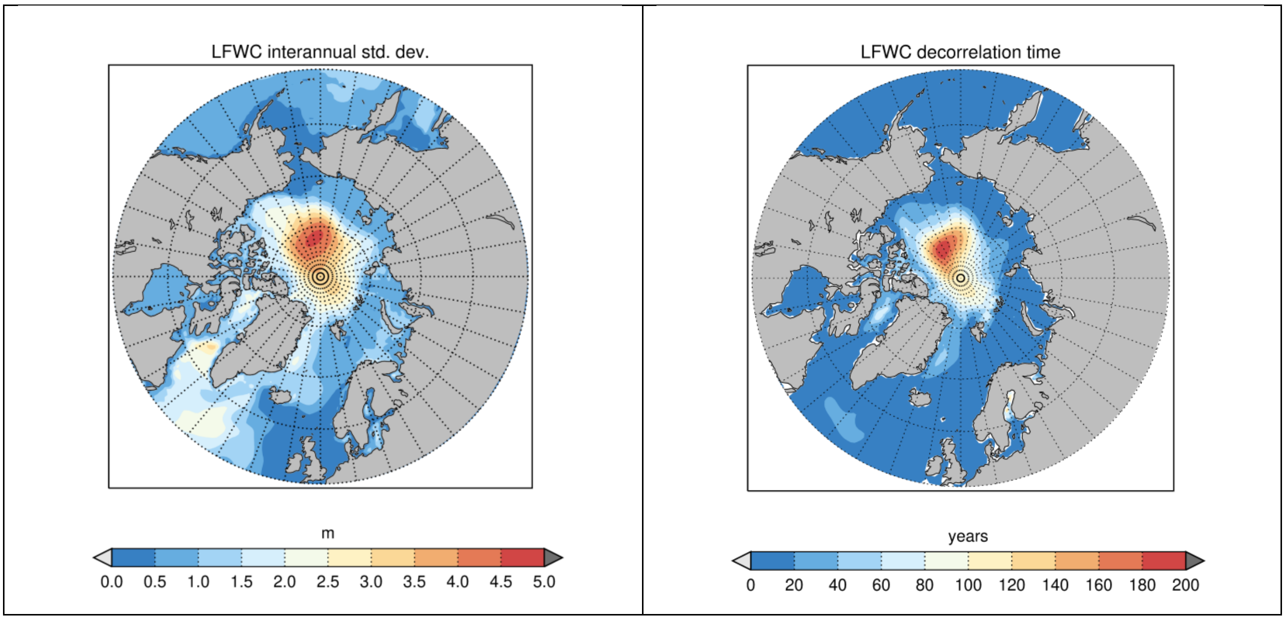

Figure 3. Spatial distribution of the variability of vertically integrated liquid freshwater (LFWC). Interannual standard deviation (left) and decorrelation time (right) is shown.

The pattern of variability shares similarities with the model climatology of liquid ocean freshwater (not shown). Largest variability is found in the central part of the Arctic Ocean connected to the model analogy to the Beaufort Gyre. These parts also exhibit very large decorrelation times of up to 200 years.

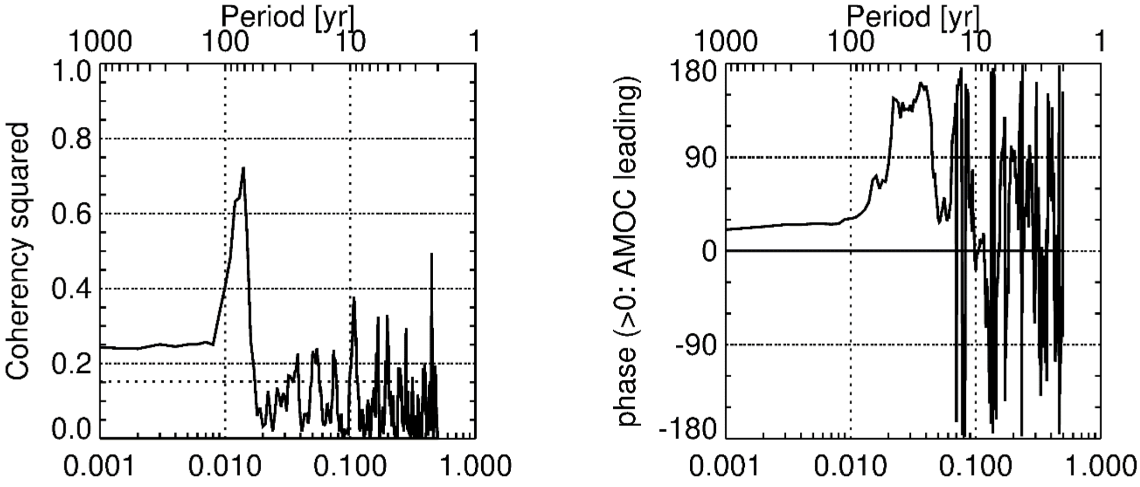

Figure 4. Squared coherency between AMOC strength at 30° N and Arctic Ocean total LFWC (left) and associated phase (right). The dotted line in left panel is 10 % significance limit.

The squared coherency between the strength of the AMOC at 30° N (Figure 1) and the total LFWC of the Arctic Ocean (Figure 2) is shown in Figure 4. Here is noted a distinct peak with a period around 80 years; this points to some quasi-oscillatory behaviour with AMOC potentially leading the total LFWC (Figure 4, right). A dynamic explanation for this relationship will need to be developed if robust (strong AMOC phase leads elevated LFWC).

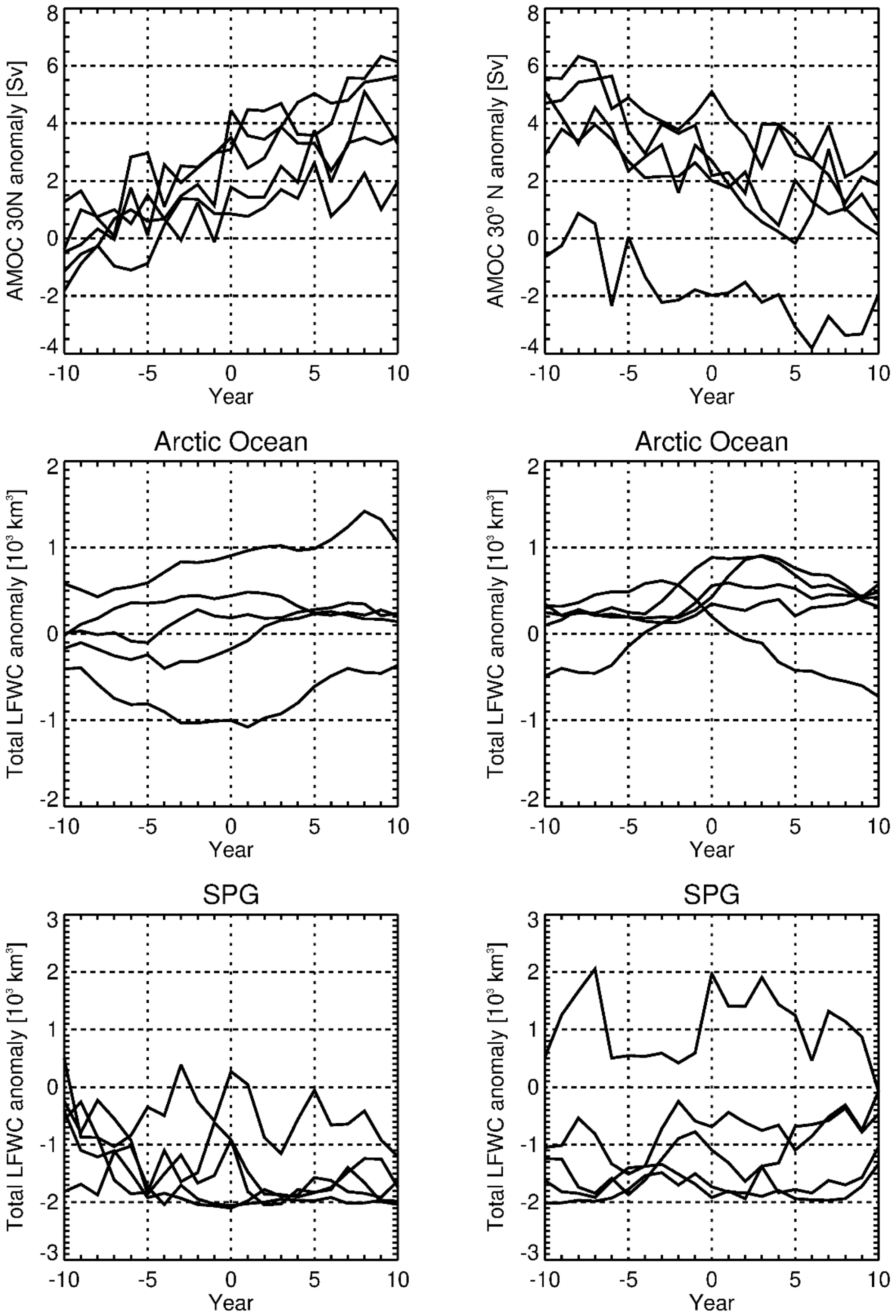

Figure 1. Composite analysis for the five numerically largest positive (left panels) and negative (right panels) trends of the AMOC strength at 30° N, estimated over a 21 year period. Panels in upper row show the segments of the actual AMOC strength. Middle and lower panels show corresponding segment of the total LFWC (middle) of Arctic Ocean and the subpolar North Atlantic (bottom).

Also, a composite analysis of the long term AMOC tendencies has been carried out; results are shown in Figure 5. This analysis does not give any clear results. However, for an increasing AMOC strength, there are signs of increasing total LFWC in the Arctic Ocean (see also Figure 4), for decreasing AMOC strength; the related changes in LFWC of the Arctic Ocean are not very systematic. More robust results of a composite analysis have been obtained using a composite analysis of the tendencies in total Arctic Ocean LFWC in earlier versions of the coupled model (CMIP5, not shown) and on shorter time-scales. It is possible that the pronounced and unsupported multi decadal AMOC variability in the CMIP6 preindustrial control simulation analysed here masks other underlying mechanisms.

# 5 Processes at the Iceland Faroe Ridge and subpolar freshening

In understanding and explaining recent changes in the eastern North Atlantic including pronounced freshening, we make use of a range of observational data. This includes fixed instrumented moorings (OSNAP) over satellite altimetry (CMEMS), drifter buoys (NOAA / AOML) and hydrographic data from central monitoring lines (e.g. Ellet Line, OSNAP, Icelandic monitoring). Meteorological reanalysis data (ERA5 / ECMWF) are further included in an integrated analysis (see Hansen et al., 2021).

We show that during the 2014-2018 the Iceland Basin became extraordinarily fresh, characterised by surface salinity lower than previously seen in a 120-year long time series. During those years, conditions for a diversion of water from the south Iceland shelf into the Iceland Basin were particular favourable. The event has previously been explained by unusual winter wind stress patterns that diverted freshwater from the western subpolar north Atlantic to the eastern basin and caused a zonal shift of the subpolar front. From the available observations, we show that the low-salinity signal near the surface was in fact locally reinforced in the central Iceland Basin by anomalous diversion of low-salinity water originating in the shallow shelf areas south of Iceland and that this can help explain why the surface salinity of the Iceland Basin became so exceptionally low. The diversion was generated by anomalous wind conditions over the Iceland Basin and caused slightly enhanced freshening of the warm waters crossing the Greenland-Scotland Ridge from the Subpolar North Atlantic into the Nordic Seas. These results are submitted for publication (Hansen et al. 2021) and not reported in detail.

Also, a number of historical and new hydrographic data are used to assess the possible existence of cold deep ocean currents between Iceland and the Faroe Islands. This is ongoing work where also current meters have been deployed at carefully selected sites May 2020 for retrieval summer 2021 by our collaborators at the Faroese Institute for Marine Research, FAMRI. Planning of these field activities is a component of our collaborative research but executed solely by our partners at FAMRI. To deliver the missing data on deep overflow across the Iceland Faroe Ridge, two oceanographic ADCP (Acoustic Doppler Current Profilers) moorings were deployed in May 2020. In addition, hydrographic surveys on cruises in both May 2020 and June 2020 (#2020 and #2024) have been conducted in support of the fixed point ADCP mooring deployments. It is noted that the preparations and planning of the experiment have been impacted by the Covid-19 lockdown; planned NCKF workshops between FAMRI and DMI with the purpose of reviewing available data has been replaced by on-line meeting; FAMRI succeeded despite lockdowns to purchase the critical batteries for two instruments and prepare the trawl protecting concrete frame needed for the deployment in the most heavily fished area; As the preparations were completed already in May, the deployments were scheduled for the first upcoming cruise #2020 May 2020, in fact earlier than planned.

Based on the available data from the Iceland Faroe Ridge, it was decided to deploy the ADCP and loggers at a deep position occupied by overflow water in Faroese territorial waters due east of a bank at the central part of the Iceland Faroe Ridge. The available bathymetric data indicate a relatively wide area with depths exceeding the average conditions at the ridge. On the cruise, full depth profiles of temperature and salinity (CTD profiles) were measured along the Iceland Faroe Ridge to the position of the planned deployment and across the ridge. This extends/complement the standard hydrographic section from Mykines and Northwest along the ridge (Figure 6). The preliminary analysis of the CTD data from these two cross sections across the ridge indicate that water with overflow characteristics (cold and dense) is present at the position of the planned mooring sites for the ADCP's and also downslope (south). Based on this we are optimistic and expect to monitor the strength of at least part of the 'missing' overflow across the Iceland Faroe Ridge and contribute new data to understand the large scale circulation and exchanges with the Arctic.

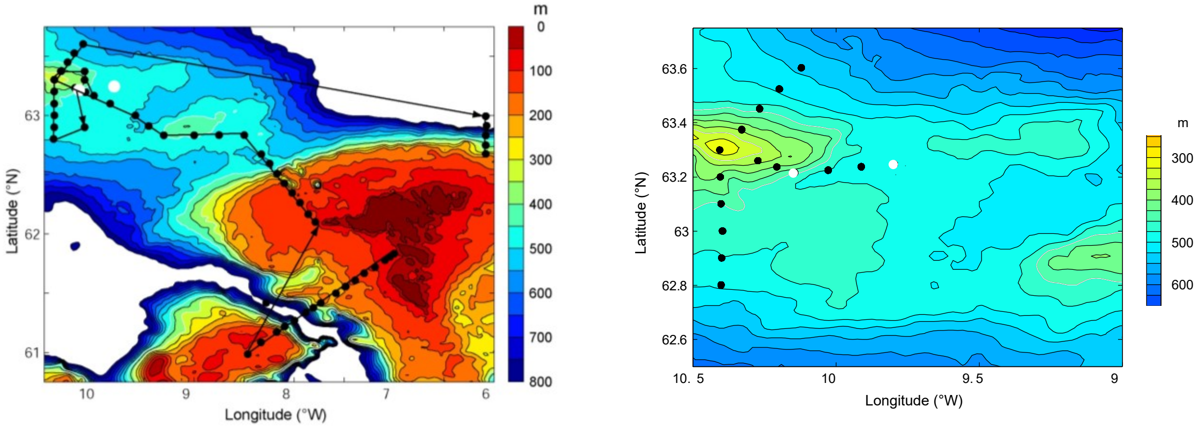

Figure 6. Cruise track (#2020, left) and CTD stations (black dots) on the Iceland Faroe Ridge for two cruises #2020 (left) and #2024 (right). White dots indicate the positions of the two new moorings, towards west the ADCP with trawl protecting frame and towards east the ADCP on a classical mooring design.

In parallel with the observational based assessments and field activities, a new ocean model asset has been developed at DMI based on the ocean model engine NEMO (Nucleus for European Modelling of the Ocean). This enables us resolve better the details of the current systems and in particular their interactions with the complex bathymetry at the Iceland Faroe Ridge. We envision that this can also result in more reliable model based estimates of ocean transports including heat exchange with the Arctic. The specific tool is a high-resolution model setup for the Iceland-Faroe-Ridge with NEMO-AGRIF (Madec et al 2019, v4.0). The high resolution (~3 km) model domain is set up for the area around the Iceland-Faroe-Ridge. It is nested into a coarser (~10 km) large scale North-Atlantic/Arctic model domain using the AGRIF feature (Adaptive Grid Refinement In Fortran) of NEMO. AGRIF enables a 2-way communication between the coarse "parent" grid and the nested "child" grid such that the child domain receives its lateral boundary conditions from the parent grid and that high-resolution model data from the child are aggregated and passed back to the parent grid at every time step.

For the IFR setup we use a refinement factor of 3 both in space and time, which leads to a spatial resolution of ~3 km and a time step of 200 seconds for the child domain. We created high-resolution input data like bathymetry, initial conditions and atmospheric forcing data using NEMO's NESTING tools and other software. A successful 6-month simulation with NEMO version 4.0.2 shows that NEMO-AGRIF is a useful tool to create computationally efficient high-resolution model simulations for specific target regions. Figure 7 includes a snapshot in time of sea surface temperature and salinity in the child domain and part of the coarser parent domain. Visual inspection shows how eddy features are more adequately resolved in the child domain and how the eddy activity is enhanced by the refinement. These characteristics are expected to result in better consistency between observed and simulated variability on the Iceland-Faroe Ridge (Olsen 2016). New observations on the IFR will be retrieved from already deployed moorings in 2021 and subject to intercomparison and process studies.

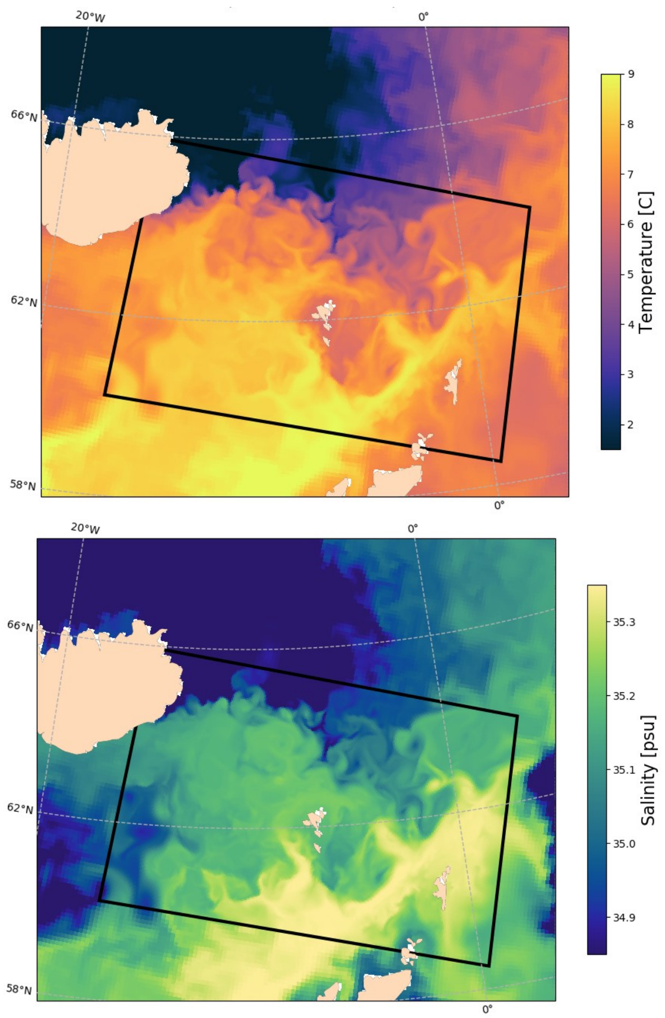

Figure 7. A living field of ocean currents and eddies seen through the surface temperature (top) and salinity (bottom) in a high resolution model nest of the region of the Iceland Faroe Ridge. The region is embedded into an Arctic-Atlantic parent domain of intermediate resolution (about 10km). The child domain has a nominal resolution of about 3km is the boarders to the parent domain are represented by the black rectangle. Data outside the rectangle are from the parent domain, both are snapshot in time.

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