Overturning circulation in the new Arctic (ArMOC)

Project leader: Marius Årthun (UoB). Partners: University of Bergen (UoB), Norwegian Research Centre (NORCE), Nansen Environmental & Remote Sensing Center (NERSC), Stockholm University (Sweden), University of Oxford (UK), Johns Hopkins University (USA), Woods Hole Oceanographic Institution (USA)

1. Excellence

The Arctic overturning circulation involves the production of water masses that are key to the global ocean circulation. The Arctic climate is, however, rapidly changing, and it is currently not known how the Arctic overturning circulation is responding. In ArMOC, we will provide new, fundamental knowledge about key oceanic processes for the Arctic overturning circulation and their sensitivity to climate change. ArMOC will accordingly lead to reduced uncertainties in projections of Arctic climate change and an improved understanding of the role of the Arctic Ocean in global ocean circulation changes.

1.1 State of the art, knowledge needs and project objectives

State of the art

The Atlantic Meridional Overturning Circulation (AMOC) - carrying warm, salty water to high latitudes - is a key component of the global ocean circulation with profound impacts on climate (Zhang et al. 2019). Dense-water formation at northern high latitudes that is a requirement to sustain the AMOC has canonically been thought to take place through deep convection in the Labrador and Greenland Seas (Buckley & Marshall 2016; Johnson et al. 2019). However, recent observations and model results suggest that the main source of dense water to the lower limb of the AMOC is Atlantic Water (AW) that gradually transforms to colder, fresher, deep water on its path through the Nordic Seas and Arctic Ocean (Figure 1; Chafik & Rossby 2019; Zhang & Thomas 2021). Whereas the AW transformation in the Nordic Seas is well studied (e.g., Mauritzen 1996; Eldevik et al. 2009), **little is known about the formation of dense water masses and corresponding overturning circulation in the Arctic Ocean**[1].

The Atlantic Water Boundary Current (AWBC) system – here defined as the combined pathways of AW in the Nordic Seas and the Arctic Ocean (Figure 1) – is a major component of the Arctic Ocean overturning circulation. Warm AW enters the Nordic Seas at the Greenland-Scotland Ridge and continues to the Arctic Ocean through the Barents Sea (Smedsrud et al. 2013) and via the Fram Strait (Schauer et al. 2008), and eventually forms a boundary current that encircles the Arctic Ocean (Coachman & Barnes 1963; Timmermans & Marshall 2020). Within the Arctic Ocean, the AWBC is cooled and freshened through ice melt, heat loss to the atmosphere, and mixing with shelf waters (Rudels et al. 2015; Pnyushkov et al. 2015). This transformation of AW produces two distinct water masses that characterize two distinct circulation branches; 1) the transformation from AW to dense overflow waters, representing the thermal overturning circulation, and 2) the transformation of AW to colder, fresher Polar waters through the input of freshwater and the en-route entrainment of ambient water, representing an estuarine (horizontal) circulation (Rudels 2010; Timmermans & Marshall 2020; Haine 2021). The thermal overturning branch eventually returns the densified AW to the deep gaps in the Greenland-Scotland Ridge, and, hence, supplies the dense overflow plumes that form the headwaters to the deep limb of the AMOC.

The Arctic climate is currently transitioning to a new, warmer, seasonally ice-free climate state (Landrum & Holland 2020), and this could have important implications for the Arctic overturning circulation. Observations suggest the development of more energetic currents (Polyakov et al. 2020; Timmermans & Marshall 2020) and the emergence of new circulation patterns (Kolås et al. 2020) under a declining sea-ice cover. The recent sea-ice retreat along the margins of the Arctic Ocean has also partially uncovered the boundary currents and left them exposed to the atmosphere in winter, allowing further modification of the AW within the AWBC during transit (Våge et al. 2018; Pérez-Hernández et al. 2019). As the transition towards a seasonally ice-free Arctic Ocean continues, more years of extreme deep mixed layers and enhanced convection can be expected, leading to a possible strengthening of the Arctic overturning circulation (e.g., Bitz et al. 2006; Brodeau & Koenigk 2016; Lique & Thomas 2018; Bretones et al. 2022). The Arctic overturning circulation could therefore be a stabilizing factor in a weakening AMOC, highlighting the importance of understanding its drivers and its response to climate change.

---

[1]The Arctic Ocean is here defined as the region bounded by the Bering Strait, Fram Strait, and the Barents Sea Opening.

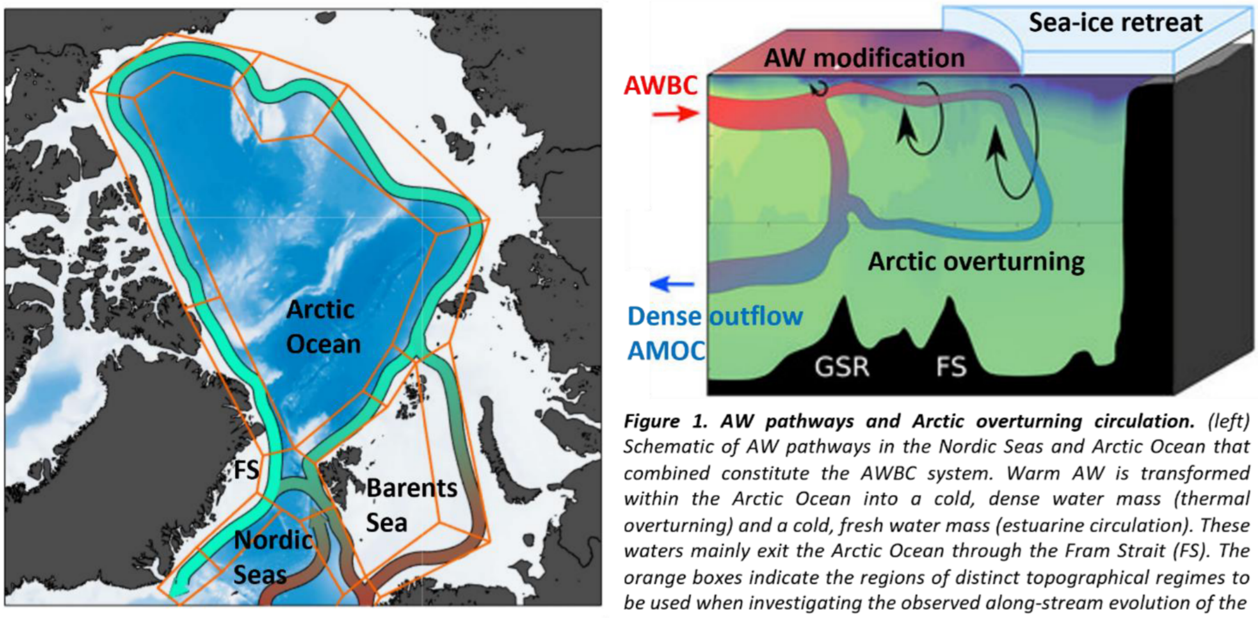

Figure 1. AW pathways and Arctic overturning circulation. *(left) Schematic of AW pathways in the Nordic Seas and Arctic Ocean that combined constitute the AWBC system. Warm AW is transformed within the Arctic Ocean into a cold, dense water mass (thermal overturning) and a cold, fresh water mass (estuarine circulation). These waters mainly exit the Arctic Ocean through the Fram Strait (FS). The orange boxes indicate the regions of distinct topographical regimes to be used when investigating the observed along-stream evolution of the AWBC (WP1). (right) Conceptual picture of the Arctic (thermal) overturning circulation (adapted from Bretones et al. 2022). The resulting dense outflow across the Greenland-Scotland ridge (GSR) feeds the lower limb of the AMOC and is thus important for the global ocean circulation.* ***ArMOC will improve our understanding of how the rapidly changing Arctic climate impacts the pathways and modification of AW (WP1-2) and how this is manifested in the Arctic overturning circulation (WP3) using new data and novel methods.***

Knowledge needs

Under anthropogenic warming a weakening of the AMOC is found in most climate models (Weijer et al. 2020). **Present and future changes in Arctic overturning, however, remain virtually unexplored**, despite climate change being most pronounced in this region. Previous modeling efforts have identified the emergence of new areas of deep convection in the Arctic Ocean as a source of Arctic overturning changes (e.g., Bitz et al. 2006; Bretones et al. 2022), but the interactions with the AWBC have not been resolved in these models. It is therefore not known how the Arctic overturning circulation will respond to changes in AW modification and associated dense waters along the AWBC. As AW modification represents a key component of the Arctic overturning circulation (e.g., Zhang & Thomas 2021), this is a particularly important knowledge gap at present. It is also **not known whether the Arctic overturning circulation has the potential for undergoing rapid changes or collapse**. The overturning circulation patterns in the Arctic Ocean (thermal and estuarine) are both sensitive to changes in the AW inflow, freshwater input, and air-sea heat fluxes, all of which are expected to change under global warming (Årthun et al. 2019; Shu et al. 2021; Zanowski et al. 2021; Moore et al. 2022). A conceptual model of the Arctic overturning suggests that a collapse of the estuarine circulation is possible in a warming climate (Haine 2021), but this has not been assessed for more realistic models. *ArMOC will close these knowledge gaps by providing a first quantification of the Arctic overturning circulation in present and future climates using the approach of thermohaline streamfunctions (WP3; Objective SO3).*

A fundamental understanding of the complete AWBC system is lacking, and to date only regional investigations have been undertaken (e.g., Pnyushkov et al. 2015; Våge et al. 2016; Li et al. 2020). The pronounced retreat of sea ice (Onarheim et al. 2014) and increasing influence of AW has characterized climate shifts in regions north of Svalbard (Polyakov et al. 2017) and in the Barents Sea (Årthun et al. 2012). The AWBC thus plays a crucial role in propagating and effectuating the ongoing "Atlantification" in the Arctic climate system. It is, however, not known how enhanced AW modification associated with sea-ice loss and increased ventilation (Våge et al. 2018; Pérez-Hernández et al. 2019) impacts the properties of dense waters formed along the AWBC. *ArMOC will close this knowledge gap through a comprehensive analysis of modern and historical observations along the AWBC pathway, including new, unique wintertime measurements from Argo floats, and through high-resolution state-of-the-art ocean reanalyses (WP1; Objective SO1).*

Furthermore, it remains **uncertain and unexplored how the AW pathways could change in a warmer and ice-free Arctic**. The loss of sea ice increases the exposure of the underlying ocean to the atmosphere which may lead to regional changes in ocean circulation pathways and their strength. Atmospheric circulation changes in a warming climate (Harvey et al. 2020) could also affect the relative strength of the AW pathways (e.g., Muilwijk et al. 2019). Such circulation changes could have important implications for AW modification along the AWBC and, hence, impact the Arctic overturning circulation. For example, any changes in the relative amount of AW entering the Arctic Ocean through the Barents Sea and Fram Strait, respectively, will have a direct impact on the properties of Arctic dense waters (Schauer et al. 1997). Understanding potential future changes in the advective pathways and the associated time scales and modification of AW in the Arctic Ocean is therefore an essential prerequisite for understanding changes in the Arctic overturning circulation. *ArMOC will close this knowledge gap by performing, for the first time, a multi-model Lagrangian analysis of AW pathways (WP2; Objective SO2).*

Project objectives

The primary objective of ArMOC is to understand how present and future Arctic climate change impacts the Arctic overturning circulation, which feeds the lower limb of the AMOC. We will achieve this through the following secondary objectives:

(**SO1**) Quantify changes in AW modification along the AWBC.
(**SO2**) Identify changes in AW pathways in present and future climates using Lagrangian simulations.
(**SO3**) Determine the effects of a changing climate on the Arctic overturning circulation.

1.2 Research questions and hypotheses, theoretical approach and methodology

The principal hypotheses of ArMOC are:

H1: Arctic dense-water production along the AWBC increases as sea ice retreats and surface heat loss increases over the new open ocean regions.
H2: Future circulation changes along the AWBC lead to a larger fraction of AW entering the Arctic Ocean through the Barents Sea.
H3: A changing Arctic Ocean leads to a strengthened thermal overturning circulation and a weakened estuarine circulation.

To test these hypotheses, the project relies on the coordinated analysis of observations, ocean reanalyses, numerical models, and their intercomparison – an approach the project team is competent with (see *CVs*). As emphasized in the Arctic Report Card 2020 (Holland et al. 2020), **integrating models and observations – as in ArMOC – is key to better predict a changing Arctic**.

The scientific challenges to be addressed in this project are detailed in the form of three work packages (WPs) below. The specific approaches and methodology are described under each WP.

WP1 Observed variability and dynamics of the Atlantic Water Boundary Current system

WP1 will focus on the observed along-stream evolution of the AWBC and its temporal variability. We will investigate the locations and processes of AW modification, the structure and baroclinic transport of the current, and the spreading of AW into the interior Arctic Ocean. To facilitate an analysis of observed spatiotemporal changes along the AWBC, the data (see *Data* below) will be subdivided into several regional boxes along the AWBC pathway that correspond to distinct topographical regimes (Fratantoni & Pickart 2007; Figure 1). This represents an innovative way to investigate the structure and properties of the AWBC. This analysis will also form an observational benchmark for the simulations in WP2. To complement existing hydrography and to obtain detailed information on the spatiotemporal evolution of the AW, we will also analyze measurements from two Argo floats that we will deploy within the AWBC north of Svalbard.

We will furthermore investigate the modification of AW during periods of different climatic states and examine whether dense waters have formed more effectively along the AWBC in recent years. While the cooling and transformation of AW in the Nordic (Mauritzen 1996; Eldevik et al. 2009; Bosse et al. 2018) and Barents Seas (Smedsrud et al. 2013; Barton et al. 2018; Docquier et al. 2020) is fairly well understood, the AWBC in the Nordic Seas is an integral part of the entire AWBC system and represents the upstream conditions for AW modification in the Arctic Ocean. The ambition of this holistic analysis is thus to produce the first comprehensive observational synthesis of the entire AWBC system around the Nordic Seas and Arctic Ocean, from inflow across the Greenland-Scotland Ridge to exit through Denmark Strait. To supplement the observations, the variability and dynamics of the AWBC will be further detailed in a medium- (12km; TOPAZ4) and a high-resolution (4km; GLORYS12) ocean reanalysis (Table 1). Observations and results from the ocean reanalyses will also be compared with the Norwegian Earth System Model (NorESM2), providing a valuable evaluation of the latter and an assessment of the AWBC in models with different resolutions. *WP1 will accordingly test H1 and address objective SO1.*

WP2 Atlantic Water pathways and transformation in a hierarchy of models

To further investigate the transformation of AW within the Arctic Ocean we will in WP2 perform Lagrangian simulations for present and future climates using the TRACMASS (Döös et al. 2017; see also *Data* below) Lagrangian particle-tracking tool together with output from the high- and low-resolution models. Previous applications of Lagrangian models in the Arctic Ocean have provided novel insights into advective pathways (Karcher & Oberhuber 2002; Lique et al. 2010; Kelly et al. 2019). We will release particles within the AWBC at different locations and at different times (historical and future) and run forward in time (10-30 years to capture the main circulation pathways of AW; Wefing et al. 2021) using the models' daily velocity, potential temperature, and salinity fields. We will in particular investigate whether climate change is altering the relative importance of AW pathways, or even opening up new ones, and to what extent this has implications for AW modification and dense-water properties within the Arctic Ocean. Changes in the transformation of AW into either surface or dense waters will be interpreted with respect to changes in the overturning circulation (WP3). We will furthermore determine to what extent future changes in AW pathways and modification are sensitive to model resolution. Improved representation of AW modification in higher-resolution models has been shown for the Barents Sea (Docquier et al. 2020). A clean comparison of different resolutions is limited to NorESM2, as different ocean models and reanalyses have different biases (e.g., Shu et al. 2019). TRACMASS simulations will, however, also be performed for the ocean reanalyses (GLORYS12, TOPAZ4) and the high-resolution coupled model CESM-HR to assess AW pathways and transformation also in higher resolution models that better resolve the AWBC. *The analysis of WP2 will test H2 and address objective SO2.*

Model/reanalysis	Resolution	Historical	Future	TRACMASS
NorESM2-MM	1° (daily)	1850-2014	2015-2100	Yes
NorESM2-MH	1/4° (daily)	1850-2014	2015-2100	Yes
CESM-HR	1/10° (monthly)	1850-2005	2006-2100	Maybe*
GLORYS12	1/12° (daily)	1993-2020	N/A	Yes
TOPAZ4 (reanalys.)	12 km (daily)	1991-2020	N/A	Yes
TOPAZ4 (forecast)	12 km (daily)	Real-time	N/A	Yes

***Table 1**. **Model and ocean reanalysis used in ArMOC.** Future simulations are based on the RCP8.5/SSP585 scenario. *see text p.6 for description.*

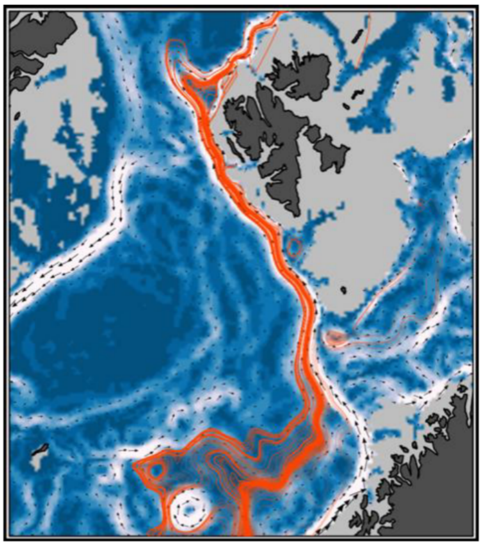

***Figure 2. AW pathways in a high-resolution simulation.** Trajectories of Lagrangian particles (red) of a 5-year simulation by TRACMASS with climatological GLORYS12 output on a 1/12° grid. The particles (only approx. 400 for demonstrative purposes) are released north of the Iceland-Scotland ridge between 180 m and 200 m (AW depth). Vectors and shadings illustrate the current speed at 200m depth. This preliminary analysis demonstrates the ability of the project team to successfully implement TRACMASS (WP2) and the ability of GLORYS12 to represent the AWBC well.*

WP3 Arctic overturning circulation

In WP3 we will quantify the mean state and variability of the Arctic overturning circulation, as well as its projected response to anthropogenic warming. Both the thermal and estuarine overturning branches (Haine 2021) will be considered. The meridional overturning circulation is commonly calculated by averaging oceanic velocities at constant latitude and depth. This approach describes the net vertical and meridional motion and is valid in regions where properties are reasonably homogeneous at constant depth and latitude. For the Arctic Ocean, however, where no zonal boundaries exist, this approach does not capture the actual overturning. Here we will adopt an alternative approach by using the thermohaline streamfunction in temperature-salinity (TS)-space (Döös et al. 2012; Zika et al. 2012; Berglund et al. 2021). The thermohaline streamfunction describes the volume flow in TS-coordinates and shows the conversion of temperature and salinity through the whole ocean interior, including both deep and surface waters. Analyzing volume transport in TS-space will allow us to identify to what extent variability and trends of the overturning circulation are driven by changes in heat and freshwater forcing. The usefulness of considering Arctic water mass transformation in TS-space has been demonstrated by e.g., Pemberton et al. (2015) and Lambert et al. (2019). These studies, however, did not consider the overturning circulation.

The Arctic overturning circulation will be investigated by thermohaline streamfunction approaches from both Eulerian and Lagrangian perspectives. The Eulerian thermohaline streamfunctions will be calculated from the models used in WP1-2 (Table 1). We will thus be able to investigate the sensitivity of the Arctic overturning circulation to model resolution and future change. The identified differences in overturning will furthermore be interpreted with respect to the results in WP1 and WP2 - Atlantic water pathways and transformation - which is a key factor in the Arctic overturning (Rudels 2010; Haine 2021). The Lagrangian thermohaline streamfunctions (e.g., Berglund et al. 2021) will be computed from the TRACMASS simulations in WP2. Using Lagrangian trajectories allows for analyzing specific components of a larger circulation, i.e., separating water mass transformations in the Arctic Ocean from the adjacent oceans in TS-space.

The future changes in overturning branches inferred from the above analysis will be interpreted with respect to the competing influences of Atlantic inflow and air-sea-land fluxes of heat and freshwater. This analysis will also include other CMIP6 models, in addition to NorESM2. We will furthermore compare the future evolution of the Arctic overturning branches and their sensitivity to heat and freshwater forcing with that inferred from the analytical model of Haine (2021) which suggests a possible collapse of the estuarine circulation in a warming climate. *The above analysis will accordingly test H3 and address objective SO3.*

Data

Hydrographic observations. To assess the variability and dynamics of the AWBC (WP1) we will analyze hydrographic data (temperature and salinity observations) and current measurements from recent/ongoing field campaigns (e.g., the Nansen Legacy project, MOSAiC, NABOS, and Synoptic Arctic Survey). Recent observations will be supplemented by the Unified Database for Arctic and Subarctic Hydrography (UDASH; Behrendt et al. 2018), containing all publicly available data collected by ships, ice-tethered profilers, profiling floats, and other platforms between 1980 and 2015. Two Argo floats will also be deployed in the AWBC north of Svalbard during autumn/winter 2024 providing new, unique data to the project from an area nearly devoid of wintertime measurements. The exact deployment locations will be strategically determined based on the timing of ongoing cruise activity in the area (related to e.g., the Nansen Legacy project) to ensure that the floats sample the open-water portion of the boundary current during the wintertime convection period.

NorESM2. The Norwegian Earth System Model version 2 (NorESM2; Seland et al. 2020) is among the CMIP6 models with the highest overall performance score (Fasullo et al. 2020). NorESM2 uses potential density as the vertical coordinate in its ocean model (BLOM). This ensures excellent conservation of water mass properties and is therefore optimal for the analysis in ArMOC. We will use NorESM2 with two ocean resolutions (Table 1), NorESM2-MM (1° ocean) and NorESM2-MH (1/4° ocean), corresponding to a nominal grid size in the Arctic of 40 km and 10 km, respectively. Both historical and future (SSP585) simulations will be analyzed, and we will rerun parts of these simulations (see *Lagrangian simulations* below) to provide the necessary daily 3D fields for the offline Lagrangian trajectory simulation (WP2).

TOPAZ4 is a coupled ocean/sea ice operational data assimilation system developed at project partner NERSC (Sakov et al. 2012). The ocean model (HYCOM) has a horizontal resolution of 12 km in the Arctic. TOPAZ4 provides 10-day real time ocean forecasting and a reanalysis (1991-2020) through the Copernicus Marine Service. The TOPAZ4 reanalysis has been extensively used and validated for the Arctic and sub-Arctic region (Xie et al. 2017; Chatterjee et al. 2018). Derived Lagrangian trajectories from the real-time TOPAZ4 forecast products (WP2) will be used in combination with the Argo observations in WP1.

GLORYS12 is a coupled ocean/sea ice reanalysis at 1/12° horizontal resolution (4 km in the Arctic) covering 1993-2020 (Lellouche et al. 2021). The reanalysis is based on the NEMO ocean model and forced by atmospheric reanalysis (ERA-Interim). The horizontal resolution is eddy-resolving throughout much of the Arctic Ocean, though only eddy-permitting on the shelves. GLORYS12 performs well in the Arctic region, e.g., in terms of volume transport through the Fram Strait and Barents Sea (Lellouche et al. 2021). GLORYS12 is available through the Copernicus Marine Service.

CESM-HR is a high-resolution configuration of the Community Earth System Model (CESM) with a nominal horizontal resolution of 1/10° for the ocean and sea-ice models (Chang et al. 2020). A 250-year historical and future climate simulation from 1850 to 2100 is freely available. CESM-HR outputs are monthly averages which may pose some limitations on the accuracy of the Lagrangian analysis (discussed below in *Risk assessment*).

CMIP6 model data are freely available from the Earth System Grid Federation (ESGF). A local replica of necessary variables is freely available on the National Infrastructure for Research Data storage (NIRD) infrastructure through the NFR KeyCLIM project.

Lagrangian simulations. To assess the pathways and modification of AW within the Arctic Ocean we will perform Lagrangian simulations for present and future climates using the TRACMASS (Döös et al. 2017; http://tracmass.org/) Lagrangian particle-tracking tool together with output from the high- and low-resolution models (Table 1). Temperature, salinity, and transport will be stored along the trajectories, from which we can derive e.g., transit times, water mass transformation, and Lagrangian thermohaline streamfunctions. TRACMASS has already been implemented for the NEMO-based GLORYS12 dataset (Figure 2). TRACMASS has also previously been used for the Arctic Ocean (Crews et al. 2019) and is thus demonstrated suitable for the proposed analysis. For GLORYS12 and TOPAZ4 the full historical simulations will be considered. For NorESM2, we will focus on three historical periods (1990-1999, 2000-2009, 2010-2019) and three future periods (2030-2039, 2060-2069, 2090-2099) to balance computational and storage load related to the daily 3D oceanic fields.

Analytical model of the Arctic overturning. This conceptual model developed by project partner Thomas Haine (Haine 2021) specifies the strengths and thermohaline properties of the estuarine and thermal overturning branches. The Matlab code is publicly available.

Risk assessment and ethical issues

The project is built on novel hypotheses (H1-H3) and well-defined tasks whose examination and eventual resolution will move the field significantly forward (see *Impacts*). Although ambitious, ArMOC is based on a feasible scientific approach. To mitigate risk the project relies on a wide range of tools, including observations and data from numerical models of different complexity. The project members are expert users of the tools and methods planned for the project. Through its affiliation with the Bjerknes Centre the project has strong resilience to unforeseen personnel changes. Possible risks and proposed mitigations measure are:

Model data and Lagrangian simulations. ArMOC relies mostly on the analysis of available numerical simulations and the risk of rerunning NorESM2 to gain daily outputs is minimal as project members carry out such tasks regularly (He, Nummelin). The implementation of TRACMASS has already been achieved for the NEMO-based GLORYS12 (Y. He; Figure 2), and the risk is therefore low associated with implementing TRACMASS in NorESM2 and TOPAZ4. The risk is further reduced by inclusion of TRACMASS developer Prof. Döös as an international partner. The project team also includes NorESM2 developers (He and Nummelin) and has direct communication with TOPAZ4 developers at NERSC (He and Xie). The monthly averaged CESM-HR output is not optimal for Lagrangian analysis. It has, however, been shown that good trajectory accuracy can be achieved by increasing the timestep of the Lagrangian simulation at affordable computational cost (Döös et al. 2017). We will therefore test and assess the performance of TRACMASS with CESM-HR data before proceeding with more detailed Lagrangian analysis (WP2, hence marked as “Maybe” in Table 1). The monthly output is not an issue in WP1 or WP3.

Observations. There is a limited number of hydrographic profiles in some areas along the length of the AWBC system, in particular in the Russian sector of the Arctic Ocean (Figure 1). If data scarcity becomes an insurmountable problem, we will have to rely to a greater extent on ocean reanalysis products (Table 1 and others such as the Arctic Subpolar Gyre State Estimate; Nguyen et al. 2021) and the high-resolution numerical simulations. Risk associated with deploying new Argo floats is associated with the expulsion of the floats from the AWBC. Deploying two floats at different locations in the AWBC north of Svalbard will add some redundancy in case one of the floats drifts into the interior basin. While Argo measurements from the interior basin will still provide context for our planned analyses, trajectories from previous deployments in this region during summer indicate that the floats predominantly remain within the AWBC.

Ethical issues and environmental impact. The research performed by the participating institutes is regulated by and complies with high ethical standards, including the duty of honesty in research as well as responsibility to colleagues, the environment, and society in the widest sense. There are no undesirable effects from carrying out the project, on human and animal health, climate and the environment, and society at large. Some traveling is unavoidable and necessary for the successful implementation and communication of the project. The environmental impact from deploying new Argo floats is minimized by taking advantage of existing cruise activity. The institutions involved in this project have an equal gender policy. Three of the project members are female, and female candidates will be particularly encouraged to apply for the project's recruitment position.

1.3 Novelty and ambition

ArMOC will provide new knowledge about the Arctic overturning circulation in present and future climates by using the novel approach of thermohaline streamfunctions. No prior study has quantified both the estuarine and thermal overturning branches in the Arctic using this approach. ArMOC will thus provide a step-change in our understanding of the Arctic overturning circulation and how it is expected to change in a warming world. This will **shed new light on how the overturning circulation in the Arctic Ocean influences the future weakening of the AMOC.**

ArMOC will build a comprehensive understanding of the entire AWBC system around the Nordic Seas and the Arctic Ocean. This will be based on both observations and high-resolution reanalyses. While regional investigations have described the general properties of the AWBC system, recent improvements in oceanographic datasets now present an exceptional opportunity to achieve a fundamental advancement, through a comprehensive analysis of modern and historical observations from strategically located areas. State-of-the-art ocean reanalyses, such as TOPAZ4 and GLORYS12, now also have sufficient horizontal resolution required for an investigation of water mass transformation processes in the AWBC (Athanase et al. 2020). A fundamental understanding of the entire AWBC system, as provided by ArMOC, is **required to confidently predict its behavior in a changing climate**.

Lagrangian simulations will provide new insights on AW pathways and transformation within the Arctic Ocean and whether this is expected to change under future global warming. ArMOC will perform Lagrangian simulations using a hierarchy of model simulations and reanalyses (Table 1). Such a multi-model Lagrangian analysis - for present and future climates - has previously not been performed. Our simulations will also provide new knowledge on how model resolution influences AW pathways and their future change.

New, unique wintertime measurements from Argo floats within the AWBC will be obtained in ArMOC. Presently, hardly any wintertime data exists within the AWBC in the Arctic Ocean. In ArMOC, daily hydrographic profiles will be obtained in the AWBC north of Svalbard where loss of sea ice has exposed new stretches of the AWBC to the atmosphere. These data will form the basis for a novel, detailed analysis of the water mass transformation and mixed-layer evolution of the AWBC. The joint analysis of the Argo drift trajectories with the modeled Lagrangian particles highlights the synergetic nature of observations and modeling in ArMOC.

2. Impact

2.1 Potential for academic impact of the research project

The proposed project will advance the state-of-the-art on major aspects of broad scientific importance:

1) ArMOC will lead to **an improved understanding of the role of the Arctic Ocean in large-scale ocean circulation changes**, and, hence, the global climate system. Much uncertainty remains about how and why the large-scale ocean circulation (e.g., AMOC) is changing and how it will evolve in the future (IPCC 2021). As the Arctic overturning circulation produces water masses that are key to a healthy AMOC, quantifying how a warmer and ice-free Arctic Ocean impacts the Arctic overturning circulation is essential to understand future AMOC changes.

2) ArMOC will lead to **increased predictability and reduced uncertainty associated with key processes in the Arctic Ocean.** Presently, it is not clear whether the retreating ice edge exposing the AWBC to the atmosphere will result in more or less Arctic dense-water formation. ArMOC will provide new, fundamental knowledge about water mass transformation processes along the AWBC system, which is a prerequisite for understanding how dense-water formation and, hence, the Arctic overturning circulation may be impacted by a changing climate. An improved mechanistic understanding will also help predict under what circumstances the Arctic overturning circulation is susceptible to possible collapse or irreversible changes.

3) ArMOC will **reduce uncertainties in projections of Arctic climate change**. Future projections of Arctic climate change and its communication to decision-makers are commonly based on coarse resolution models.

Through dedicated comparisons of high- and low-resolution models ArMOC will provide improved estimates of model uncertainty needed to better understand and communicate future climate change in the Arctic region. ArMOC will provide important new results on the performance of climate models and ocean reanalyses in the Arctic, and thus **help guide model development in the Arctic**.

4) Analysis of how the present state of the Arctic Ocean compares with previous changes will **put data from recent field campaigns (e.g., MOSAiC) into the broader context of global change**. In addition, the model analysis in ArMOC will provide longer-term temporal and broader spatial context for the observations. This is important to correctly interpret observed changes and to identify potential monitoring gaps.

2.2 Potential for societal impact of the research project

ArMOC has many societally relevant implications. ArMOC will shed new light on the role of the Arctic Ocean in large-scale ocean circulation changes, whose potential risk of a future slowdown is a matter of great societal interest (IPCC 2021). Increased understanding and predictability of key processes in the Arctic Ocean and reduced uncertainty in future projections of Arctic climate change will furthermore provide improved constraints on the impacts of climate change, which are required for society to prepare mitigation strategies or determine measures of reducing emissions to tackle climate change. Results from ArMOC will increase societal awareness of Arctic climate change and the urgency to mitigate global warming. ArMOC will accordingly address **UN Sustainable Development Goal 13** *"Take urgent action to combat climate change and its impacts"*, and **EU's Arctic Strategy** (*Climate Change and the Arctic Environment*).

A warmer and progressively ice-free Arctic Ocean also has large implications for Arctic industry (e.g., fishing and shipping) and communities (e.g., temperature change on Svalbard; Isaksen et al. 2016). By providing better knowledge on key processes in the Arctic Ocean, and their expected future development, ArMOC improves the knowledge basis for sustainable management of the changing Arctic environment and its associated resources. Implementing the TRACMASS trajectory tracking tool in TOPAZ4 will also add value to this operational forecasting system, and thus to the broad users of the Copernicus Marine Service. ArMOC thus addresses **UN Sustainable Development Goal 14**: *"Conserve and sustainably use the oceans, seas and marine resources for sustainable development"*. Societal impacts by a changing ocean, and the need to understand these changes, were also recently highlighted by the **European Academies' Science Advisory Council** (policy report, 2021).

2.3 Measures for communication and exploitation

ArMOC will target several groups of audiences:

Academic audiences will be targeted through peer-reviewed papers in leading journals of the field (e.g., Nature Climate Change, Journal of Climate) and through presentations at national and international conferences (e.g., Arctic Frontiers, EGU, Ocean Sciences). Results from the project will also be communicated to peers through more dedicated meetings/workshops such as FAMOS (Forum for Arctic Modelling and Observational Synthesis) and ASOF (Arctic sub-Arctic Ocean Fluxes), where members of the project are actively involved.

Public/decision-makers. ArMOC research will also be converted into outreach through social media and well-established collaborative channels at the Bjerknes Centre and UoB who have wide experience in communicating research to the interested public and decision-makers (see Deliverables in the online application). Outreach activities will include one podcast about each WP, published through the Bjerknes Podcast series, and a 1-week Instagram takeover of the Bjerknes account to showcase the project. UoB/Bjerknes will also help set up a project website that will present the key objectives and results of ArMOC. The project leader and group are proficient in science communication and will prepare popular science summaries of new results (minimum 1 per WP) for national media and online research, such as Norway's two most important outlets for popular science forskning.no and aftenposten.no/viten where the project team has previously published (see *CVs*). A special media story report will be prepared about the "adventures" of the Argo floats. At the end of the project, we will also prepare a popular report summarizing our key findings in Norwegian and English. Towards the end of the project, we also aim to organize an open session or side event at the Arctic Frontiers conference in Tromsø, which is a prominent meeting spot for Arctic policymakers. Such events have previously been successfully organized by the Bjerknes Centre/UoB.

Students. K. Våge, L.H. Smedsrud, H.R Langehaug regularly teach courses at UoB (e.g., Polar Oceanography) where results of ArMOC can be exploited, both in lectures and in student projects and assignments.

3. Implementation

3.1 Project manager and project group

A dedicated team has been assembled for the purpose of the 3.5-year project ArMOC, starting 1st February 2023. The project group consists of leading national and international experts with comprehensive understanding of ocean dynamics, modeling, and observations in the Arctic region. The ArMOC project group thus includes the **complimentary competence necessary to execute the project successfully**. The person months (pm) and in-kind contributions of each project member are indicated below.

Dr Marius Årthun (18 pm, UoB) will lead ArMOC. He has a proven publication record, international experience, and extensive knowledge of high-latitude ocean dynamics and atmosphere-ocean interaction from observations and models. Årthun has also gained leadership experience from other large projects, including the coordination of a Research Council of Norway – Young Research Talent Project (€1m; 2017-2020) and as WP-leader in other large national projects (e.g., Nansen Legacy, €70m; see *CV*). He is also an experienced supervisor. Årthun will lead WP3 and mentor the project's postdoc (Tasks 1.2, 2.2, 3.1-3.3).
Prof Kjetil Våge (3.5 pm in kind, UoB) will lead WP1. Våge is a leading expert in the observational analysis on water mass transformation processes in the Nordic Seas and Arctic Ocean (e.g., Våge et al. 2018; Moore et al. 2022). He is also an experienced supervisor and work package leader (Tasks 1.1 and 1.2).
Dr Yanchun He (10 pm, NERSC) will lead WP2. He is an expert in numerical modeling (e.g., He et al. 2016) and tracer simulation (e.g., He et al. 2012), and will implement the Lagrangian model (Tasks 2.1, 2.2, 3.2).
Prof Lars H. Smedsrud (3.5 pm in kind, UoB) has extensive experience in the analysis and interpretation of observations and simulations from the Arctic Ocean (e.g., Smedsrud et al. 2013) (Task 1.2 and 3.3).
Dr Stefanie Semper (12 pm, UoB) is an expert on observational analysis of the along-stream evolution of high-latitude boundary currents and their dynamics (e.g., Semper et al. 2020) (Tasks 1.1 and 1.2).
Dr Aleksi Nummelin (3 pm, NORCE) is experienced in the development and analysis of numerical models in the Arctic Ocean (e.g., Nummelin et al. 2016; Lambert et al. 2019) (Tasks 2.1 and 3.2).
Dr Helene R. Langehaug (5 pm, NERSC) has extensive experience in the analysis and intercomparison of CMIP5/6 model simulations in the Arctic-Atlantic region (Langehaug et al. 2013; 2022) (Tasks 3.1 and 3.3).
Dr Jiping Xie (1 pm, NERSC) is an expert in the TOPAZ ocean forecasting system and is the developer of the TOPAZ4 reanalysis product (Xie et al. 2017) (Task 2.1).
Benjamin Pfeil (3 pm, UoB) is the leader of the Bjerknes Climate Data Centre and will assist with data management of the project (WP1-3).
One **Postdoctoral Research Associate** (PDRA; 36 pm, UoB) will be hired through international recruitment. The PDRA will work on the simulations across the different WPs (Tasks 1.2, 2.2, 3.1-3.3) and will be mentored by M. Årthun. To ensure that the PDRA will successfully complete the Post Doc program within this project, a career development plan which includes supervision framework and qualifying activities will be prepared at the start of the employment period.

The project also involves 4 leading international experts within the core areas of the project.
Prof Kristoffer Döös (Stockholm University, Sweden): Expert on TRACMASS and the implementation and interpretation of the Lagrangian experiments that will be performed in the project (WP2). He is also skilled in the calculation and interpretation of the thermohaline streamfunctions central to WP3 (Döös et al. 2012).
Dr Robert Pickart (Woods Hole Oceanographic Institution, USA): Vastly experienced with ocean-ice-atmosphere interaction and high-latitude boundary currents. Developed the analytical method that will be employed in the analysis of the AWBC system (WP1; Fratantoni & Pickart 2007).
Prof Helen Johnson (University of Oxford, UK): Expert on ocean dynamics and the Arctic-Atlantic overturning circulation (Johnson et al. 2019; WP3), and in the analysis of Lagrangian simulations (WP2).
Prof Thomas Haine (Johns Hopkins University, USA): Expert on ocean dynamics in the Arctic region. Developed the analytical model of Arctic overturning circulation that will be used in WP3 (Haine 2021).

3.2 Project organisation and management

The research and outreach of ArMOC is divided into three WPs as outlined above. An overview of the project schedule is shown in Table 2, whereas the duration, timeline, and resources of WPs and Tasks is shown in subsequent tables. Additional deliverables related to outreach are found in the online application. The resources assigned to the WPs are aligned with the project objectives. All project members will actively contribute to ensure the scientific quality and successful completion of ArMOC. The main project team is based in Bergen, Norway, making day-to-day collaboration easy, while we have strengthened the group significantly by including four international experts in the project's core areas. Many of the group members have collaborated successfully earlier, in projects or by co-authoring peer review publications. We will utilize digital platforms, such as Microsoft Teams, for sharing documents and holding video meetings. The entire team will also gather in Bergen for annual meetings (always with the possibility of joining remotely).

WPs		2023				2024				2025				26	
Quarter		1	2	3	4	1	2	3	4	1	2	3	4	1	2
WP1	**Task 1.1**								**M1**			**D1.1**			
	Task 1.2														**D1.2**
WP2	**Task 2.1**				**M2**	**D2.1**									
	Task 2.2								**D2.2**						
WP3	**Task 3.1**									**D3.1**					
	Task 3.2												**D3.2**		
	Task 3.3														**D3.3**
PDRA															
Meeting															

Table 2. Overview of the project schedule and the duration of the different WPs and Tasks. **D**: Deliverables; **M**: Milestones.

WP1: Observed variability and dynamics of the Atlantic Water Boundary Current system (30.5 PM)					
Leader	K. Våge (0+3.5) (Person month = requested + in-kind)				
Objective	Determine the variability, dynamics, and along-stream evolution of the AWBC				
Personnel	S. Semper (12+0)	PDRA (9+0)	M. Årthun (4+0)	L.H. Smedsrud (0+2)	R. Pickart
T1.1	Analysis of observed along-path AW modification and dynamics in the AWBC.				
M.1	Deployment of Argo floats in the AWBC north of Svalbard (Q4-2024)				
D1.1	Submitted paper on observed AW modification along the AWBC (Q3-2025)				
T1.2	Determine the observed and simulated variability and trends in AW properties and the impact of sea-ice retreat.				
D1.2	Submitted paper on observed and simulated AW variability and dense-water formation in the AWBC (Q2-2026)				

WP2: Atlantic water pathways and transformation in a hierarchy of models (30 PM)						
Leader	Y. He (10+0) (Person month = requested + in-kind)					
Objective	Investigate Atlantic water pathways and modification in present and future climates using Lagrangian simulations					
Personnel	PDRA (9+0)	M. Årthun (5+0)	A. Nummelin (2+0)	J. Xie (1+0)	B. Pfeil (3+0)	K. Döös
T2.1	Perform Lagrangian simulations based on output from low- and high-resolution reanalysis data and models.					
M2	TRACMASS simulations available for models/reanalyses listed in Table 1 (Q4-2023)					
D2.1	Report on implementation of TRACMASS and code changes committed to the TRACMASS GitHub repository (Q1-2024).					
T2.2	Identify how pathways and along-path modification of AW within the Arctic Ocean will change in a warming climate					
D2.2	Submitted paper on present and future AW pathways and modification based on Lagrangian experiments (Q4-2024).					

WP3: Arctic overturning circulation (34.5 PM)						
Leader	M. Årthun (9 + 0) (Person month = requested + in-kind)					
Objective	Determine the effects of a changing climate on the Arctic overturning circulation					
Personnel	PDRA (18+0)	H.R. Langehaug (5+0)	A. Nummelin (1+0)	L.H. Smedsrud (0+1.5)	T. Haine	H.L. Johnson
T3.1	Calculate and describe the present and future strength of the Arctic overturning circulation based on thermohaline streamfunctions in a hierarchy of models.					
D3.1	Submitted paper on Arctic overturning in present and future climates (Q1-2025)					
T3.2	Calculate Arctic thermohaline streamfunctions from Lagrangian simulations.					
D3.2	Submitted paper on Arctic overturning from Lagrangian simulations (Q4-2025)					
T3.3	Assess the sensitivity of the Arctic overturning circulation to future changes in forcings and compare with the conceptual model of Haine (2021)					
D3.3	Submitted paper on the forcing and sensitivity of the Arctic overturning (Q2-2026)					

Interactions between WPs: All WPs are interconnected, but they are not critically interdependent. WP2 will provide model data to WP1 and WP3. The analysis and results from WP1,3 will, in turn, provide feedback to WP2 on model performance versus observations (WP1) and on the differences between high- and low-resolution simulations (WP1,3). WP1 and WP3 will interact on the role of the AWBC in Arctic overturning.

Research infrastructure and other resources

Data storage. We will apply for storage of ocean reanalyses and model output from the National Infrastructure for Research Data of Norway (NIRD). We have set a sufficient budget for the data storage cost needed by the service provider, Sigma2 AS (and computing resources described below, see online application). We will also use existing storage resources by in-kind contributions.

High-performance computing. We will rerun NorESM2 to obtain 60-year daily output (as described in the Data section) on Betzy, the most powerful supercomputer in Norway. For the Lagrangian simulation, we will use the NIRD Service Platform storage service, which is designed to handle large-scale data processing.

Project management. The project will be hosted by the Geophysical Institute, UoB, which is an internationally renowned institute for ocean, atmosphere, and climate research. The institute is a partner of the Bjerknes Centre for Climate Research (as are NORCE and NERSC), which is a focal point for climate research in the natural sciences in Norway, and which includes scientists with comprehensive understanding of ocean-atmosphere dynamics in the Arctic region, which will be valuable for the project. The project will be handled by project leader M. Årthun. For administrative and technical support, the project will draw on the institutions' infrastructures, which are large and well-organized.

Data management. The Bjerknes Climate Data Centre at UoB (B. Pfeil) will ensure professional stewardship of all model output generated. A data management plan will provide information on what data will be generated, it will ensure curation, preservation, and ensure open access to all results generated, including the programs and software generated by this project. The data management plan will follow the requirements as outlined by the Research Council of Norway and by the Open Research Data Pilot as required within H2020 and ensure that data is made available following the FAIR data management principles.

REFERENCES

Årthun et al. (2012). J. Climate., 25, 4736-4743
Årthun et al. (2019). J. Climate, 32, 3327-3341
Athanase et al. (2020). J. Geophys. Res., 125(10)
Barton et al. (2018). J. Phys. Oceanogr. 48(8), 1849-1866
Behrendt et al. (2018). Earth Syst. Sci. Data, 10, 1119-1138
Berglund et al. (2021). J. Geophys. Res., 126, e2021JC017330
Bitz et al. (2006). J. Climate, 19, 2437-2450
Bosse et al. (2018). J. Geophys. Res., 123(9), 6428-6448
Bretones et al. (2022). J. Climate, 35(1), 109-124
Brodeau & Koenigk (2016). Clim Dyn., 46, 2863-2882
Buckley & Marshall (2016). Rev. Geophys., 54(1), 5-63
Carmack et al. (2015). Bull Amer Meteor Soc., 96, 2079-2105
Chafik & Rossby (2019). Geophys. Res. Lett., 46, 4799-4808
Chang et al. (2020). J. Adv. Model. Earth Syst., 12
Chatterjee et al. (2018). Geophys. Res. Lett., 45(16)
Coachman & Barnes (1963). Arctic, 16(1), 8-16
Crews et al. (2019). J. Geophys. Res., 124, 267-280
Docquier et al. (2020). Front. Earth Sci., 8, 172
Döös et al. (2012). J. Phys. Oceanogr., 42(9), 1445-1460
Döös et al. (2017). Geosci. Model Dev., 10, 1733-1749
Eldevik et al. (2009). Nat. Geosci., 2(6), 406-410
Fasullo et al. (2020). Geosci. Model Dev., 13, 3627-3642
Fratantoni & **Pickart** (2007). J. Phys. Oceanogr., 37(10)
Harvey et al. (2020). J. Geophys. Res., 125(23)
Haine (2021). J. Phys. Oceanogr., 51(3), 727-744
He et al. (2012). Tellus B, 64(1), 18807-18807
He et al. (2016). Ocean Mod., 100, 31-48
Holland et al. (2020). Arctic Report Card 2020. doi: 10.25923/bx13-ja71
Isaksen et al. (2016). J. Geophys. Res., 121, 11913-11931
Johnson et al. (2019), J. Geophys. Res., 124, 5376-5399
Karcher & Oberhuber (2002). J. Geophys. Res., 107(C6)
Kelly et al. (2019). J. Geophys. Res., 124(7), 4696-4709
Kolås et al. (2020), J. Geophys. Res., 125, e2020JC016174
Lambert et al. (2019). J. Geophys. Res., 124, 302-319
Landrum & Holland (2020). Nat. Clim. Change, 10, 1108-1115
Langehaug et al. (2013). Ocean Mod., 71, 114-126
Langehaug et al. (2022). J. Climate, in press.
Lellouche et al. (2021). Front. Earth Sci., 9
Li et al. (2020). J. Geophys. Res., 125, e2020JC016197
Lique et al. (2010). J. Geophys. Res., 115(C5)
Lique & Thomas (2018). Nat. Clim. Change, 8, 1013-1020
Mauritzen (1996). Deep Sea Res., 43(6), 769-806
Moore et al. (2022). Nat. Commun., 13(1), 1-8
Muilwijk et al. (2019). J. Geophys. Res., 124, 6286-6322
Nguyen et al. (2021). J. Adv. Model. Earth Syst., 13(5)
Nummelin et al. (2016). J. Geophys. Res., 121(1), 617-637
Onarheim et al. (2014). Tellus A, 66(1), 23933
Pemberton et al. (2015). J. Phys. Oceanogr, 45(4), 1025-1050
Pérez-Hernández et al. (2019). J. Geophys. Res., 122.
Pnyushkov et al. (2015). Deep Sea Res., 101, 80-97
Polyakov et al. (2017). Science, 356, 285-291
Polyakov et al. (2020). Geophys. Res. Lett., 47 (16)
Rudels (2010). Tellus A, 62:2, 109-122
Rudels et al. (2015). Prog. Oceanogr., 132, 128-152
Sakov et al. (2012). Ocean Sci., 8(4), 633-656
Schauer et al. (1997). J. Geophys. Res., 102(C2), 3371-3382
Schauer et al. (2008). Arctic-Subarctic Ocean Fluxes, 65-85
Seland et al. (2020). Geosci. Model Dev., 13, 6165-6200
Semper et al. (2020). Nat. Commun., 11(1), 1-10
Shu et al. (2019). Clim. Dyn., 53, 5279-5291
Shu et al. (2021). Nat. Commun. 12
Skagseth et al. (2020). Nat. Clim. Change, 10, 661-666
Smedsrud et al. (2013). Rev. Geophys., 51(3), 415-449
Timmermans & Marshall (2020). J. Geophys. Res., 125(4)
Våge et al. (2016). J. Geophys. Res., 121(9), 6946-6960
Våge et al. (2018). Nat. Commun., 9, 1287
Xie et al. (2017). Ocean Sci., 13(1), 123-144
Weijer et al. (2020). Geophys. Res. Lett., 47(12)
Wefing et al. (2021). Ocean Sci., 17
Zanowski et al. (2021). J. Geophys. Res., 126, e2020JC016930
Zhang et al. (2019). Rev. Geophys., 57, 316-375
Zhang & Thomas (2021). Comm. Earth & Environ., 2(1), 1-12
Zika et al. (2012). J. Phys. Oceanogr., 42(5), 708-724

NB: References with authorship or co-authorship by project participants indicated in **bold**.