2018 7th FAMOS meeting abstracts
October 16, 2018

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Arctic sea ice melt season length in the CESM Large Ensemble

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Melt season length—the difference between the sea ice melt onset date and the sea ice freeze onset date—plays an important role in the radiation balance of the Arctic and the predictability of the sea ice cover. There are multiple possible definitions for sea ice melt and freeze onset in the CESM Large Ensemble, and none of them exactly correspond to the remote sensing definition. We first show how the mismatch between model and remote sensing definitions of melt and freeze onset limits the utility of melt season remote sensing data for bias detection in models. Then, by using the CESM Large Ensemble, we account for the role of internal variability, allowing us to assess the comparability of different melt and freeze onset definitions.

In the CESM Large Ensemble, we find that the increase in melt season length is not as large as that derived from remote sensing data, even when we account for internal variability and different definitions. At the same time, we find that the CESM ensemble members that have the largest trend in sea ice extent over the period 1979-2014 also have the largest melt season trend, driven primarily by the trend towards later freeze onsets. Our analysis explores the hypothesis that an underestimation of the melt season length trend is one factor contributing to the generally underestimated sea ice sensitivity in the CESM.

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Impacts of ocean waves on sea ice and the Polar Oceans

Sea ice retreat and opening of large, previously ice-covered areas of the Arctic Ocean, to the wind and ocean waves leads to the Arctic sea ice cover becoming more fragmented and mobile, with large regions of ice cover evolving into the Marginal Ice Zone (MIZ). The need for better climate predictions, along with growing economic activity in the Polar Oceans, necessitates climate and forecasting models that can simulate fragmented sea ice and impacts on the ocean with a greater fidelity. We present simulations performed with a high-resolution sea ice-ocean general circulation global model NEMO (stands for Nucleus for European Modelling of the Ocean) coupled with the ocean wave model output from model of the European Centre for Medium-Range Weather Forecasts (ECMWF). The wave-ice coupling includes ice break–up by waves, a new granular rheology and enhanced ocean mixing due to waves. We analyse the impact of the waves on sea ice and the upper ocean, focusing on the Marginal Ice Zone (MIZ), and examine the observed wave increase and changes sea ice fragmentation and the predicted future widening of the in the Arctic and the Bellingshausen–Amundsen Seas of the Southern Ocean. The study discusses implications of the project future changes in the sea ice and ocean for climate and forecasting and asserts their impacts on the ocean biogeochemistry and ecosystems.

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Spectral light transmittance of Arctic sea ice

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Light transmittance through Arctic sea ice has an important impact on both the ocean heat content and the ice associated ecosystem. Thus, it is crucial to investigate the optical properties of sea ice to assess the role of the surface energy budget and its change due to climate change. Measurements of spectral transmittance can be used to investigate the influence of surface and ice properties regulating radiative transfer, especially on a larger horizontal scale. Here, we concentrate on categorizing snow and sea ice based on spectral transmittance data. Transmitted radiance and irradiance are measured at the underside of sea ice using a remotely operated vehicle (ROV). The scientific payload also includes CTD, fluorometer, pH-, nitrate-, oxygen-, attenuation sensor, upward-looking single-beam sonar, and periodically a surface and under ice trawl for assessing the spatio-temporal variability of sea ice algae. Thus, data for all disciplines in sea ice research can be recorded. The main benefits using the ROV compared to point measurements are the larger spatial coverage in comparably short times and the undisturbed sampling even under very thin sea ice, with parameters all collected during the same time. Snow depth is derived from a combination of terrestrial laser scanner data and manual measurements, while ice draft is measured using the single-beam sonar. Here, we present first data from the Last Ice campaign off Alert in May 2018. This region is dominated by sea ice with a larger thickness due to dynamic thickening. We investigated different ice regimes, such as First Year Ice with a continuous thickness of about 1.5m and structured Multi Year Ice with thicknesses up to 6m over the duration of four weeks to study the differences between various ice types.

Sensitivity of submarine melting on North East Greenland towards ocean forcing

The Nioghalvfjerdsbræ (79NG) is a floating ice tongue on Northeast Greenland draining a large part of the Greenland Ice Sheet. A CTD profile from a rift on the ice tongue close to the northern front of 79NG shows that Atlantic Water (AW) is present in the cavity below with a maximum temperature of approximately 1°C at 610m. The AW present in the cavity most likely drives submarine melting along the ice base. Here, we simulate melt rates with a 1D numerical Ice Shelf Water plume model. The plume is initiated at the grounding line depth (600m) and rises along the ice base as a result of buoyancy contrast to the underlying AW. Ice melts as the plume entrains warm AW. The plume dynamics and mass, momentum, heat, and salt conservation at the ice-ocean boundary, and, hence, the melting are parameterized using an entrainment coefficient and a drag coefficient. Maximum simulated melt rates are 50 - 75m/yr within 10km of the grounding line. Within a zone of rapid decay between 10km and 20km melt rates drop to roughly 6m/yr. Further downstream, melting increases again for about 5km to approximately 15m/yr before relatively steady mean melt rates of 6m/yr are maintained. Mean and maximum melt rates increase linearly with rising AW temperature. Variability in AW properties between 1992 and 2015 are examined using an ocean state estimate (ECCOv4). Using the simulated range of AW properties (0.1 - 1.4°C at 300m depth on the shelf) in the plume model gives a range in mean melt rates along the centreline of the ice tongue between 10m/yr and 19m/yr. The corresponding freshwater flux ranges between 19km^3/yr (0.6mSv) and 36km^3/yr (1.1mSv). Our results improve the understanding of processes driving submarine melting of marine-terminating glaciers around Greenland, and its sensitivity to changing ocean conditions

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Cooling of the West Spitsbergen Current by shelf-origin cold core lenses

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The West Spitsbergen Current (WSC) cools as it flows northward along the western Svalbard shelf. While part of this cooling takes place at the ocean surface through interaction with the atmosphere, a significant amount of cooling of the WSC core takes place subsurface. Here we present observations with high horizontal resolution (around 2 km) from a Sea Explorer glider deployed in July 2017 for 14 days in the WSC offshore Kongsfjorden around 79°N. They document small lenses (less than 10km diameter) of cold (less than 3.8°C) and fresh (less than 35.2g/kg) waters in the core of the WSC. These waters come from the shelf and contribute to the cooling of the core of the WSC. Water from the shelf cascades to the bottom of the slope through diapycnal displacement. The cold and fresh lenses detached from the bottom of the slope through isopycnal displacement. Dynamics and detachment of these lenses from the shelf can be interpreted in relation with the wind regime. Strong southerly winds cause upwelling of the warm Atlantic Water (AW) onto the shelf in winter. Weak and/or northerly winds allow modified AW formed by mixing with cold waters on the shelf to cascade down the slope, leading to lenses of colder and fresher water protruding into the WSC. If theses lenses are common in the WSC, they could be contributing significantly to its cooling.

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The role of Atlantic heat transport in future Arctic winter sea ice variability and predictability

During recent decades, Arctic sea ice retreat and variability during winter have largely been a result of variable ocean heat transport. The relationship between ocean heat and sea ice anomalies has allowed for skillful predictions of winter sea ice extent, especially in the Barents Sea. Here we use the CESM large ensemble simulation to assess to what extent future Arctic winter sea ice loss is driven by Atlantic heat transport, and to disentangle internally and externally forced variability. We find that in a warming world (RCP8.5), interannual to decadal sea ice variability is predominately driven by internal variability, whereas external variability is more important for multi-decadal sea ice trends. Ocean heat transport into the Barents Sea is a major source of internal Arctic sea ice variability also in the future, and, as a consequence, ocean heat transport remains a good predictor of Arctic winter sea ice variability. The future increase in ocean heat transport is carried by warmer water as the current itself is found to weaken. The warmer Atlantic water spreads from the Barents Sea into the downstream Arctic Ocean, leading to substantial changes in sea ice thickness.

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Mechanisms of ocean heat anomalies formation in the Norwegian Sea

Ocean heat content in the Nordic Seas exhibits pronounced variability on interannual to decadal time scales. These ocean heat anomalies are known to influence Arctic sea ice extent, marine ecosystems, and continental climate. It is, however, still unknown to what extent such heat anomalies are produced locally within the Nordic Seas, and to what extent the region is more of a passive receiver of anomalies formed elsewhere. In order to address this issue, a regional heat budget is calculated for the Norwegian Sea using the ECCOv4 ocean state estimate - a dynamically and kinematically consistent model framework fitted to ocean observations from the period 1992-2015. The depth-integrated Norwegian Sea heat budget shows that approximately 50% of the interannual heat content variability is explained by ocean advection, and 50% is explained by local air-sea heat fluxes. Further spatial analysis of the individual heat budget terms indicates that ocean advection is the dominant driver of heat content variability along the Atlantic water pathway. Spatial and temporal decompositions of the advection term indicates Atlantic water inflow strength to be a major source of Norwegian Sea heat content variability, and inversely linked to the Subpolar Gyre strength.

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Hydrography of the 2017 Western Eurasian Arctic Basin, in IAOOS data and in the global Mercator Ocean system

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In April 2017, two IAOOS (Ice Atmosphere Ocean Observing System) platforms were deployed at the North Pole from the Russian ice camp Barneo. One profiler was equipped with biogeochemical sensors (RemA pack, SUNA, pCO_2 SAMI) for the first time on top of the CTD-DO sensors. CDOM, nitrate and dissolved oxygen observations are used to characterize water masses on top of the traditional T-S parameters.

The IAOOS 2017 dataset provide a physical and biogeochemical characterization of the upper 350 m Eurasian Basin, across four provinces with distinct hydrographic properties: the Amundsen Basin, the Gakkel Ridge, the Nansen Basin and the Fram Strait. Fresher and CDOM-rich surface waters in the Amundsen Basin show the influence of Siberian rivers. The data feature two distinct halocline eddies in the Amundsen Basin and two Atlantic Water (AW) mesoscale structures in the Nansen Basin and near the Fram Strait. Both halocline eddies carry surface water properties, likely generated by frontal instabilities on the shelf or by lead-induced thermohaline convection. In both AW structures, temperature and salinity vertical profiles show intrusions and staircase structures, likely generated by double-diffusive processes.

The global 1/12° Mercator Ocean operational system shows remarkable performance when compared to IAOOS physical measurements. In spite of moderate biases (0.5°C too cold in the Eurasian Basin interior, [0.5-2] g/kg too salty near the surface), the spatial and temporal representations of the water masses are consistent with the observations. The warm layer and the characteristics of the AW structures are particularly well reproduced. Model outputs are used to investigate the nature and origin of these AW structures. Although only eddy-permitting in the Arctic region, the Mercator Ocean model allowed the identification of the first structure (at 83.7°N-34.5°E) as an AW meander from the Arctic Circumpolar Boundary Current (ACBC), that turned into an anti-cyclonic AW eddy about a month after the platforms drifted away. This AW eddy propagated slightly northwestwards for 2.5 months until February 2018 when the rotation decays and its T-S characteristics erode. The second structure (at 82.8°N-3°W) likely is an AW meander/eddy of an AW recirculating branch detaching from the Yermak Plateau slope back into the Fram Strait.

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Ocean dynamics and the latitude of the sea-ice edge

Due to its high reflectivity and insulating effect on oceans, the sea-ice cover has a large impact on the climate state. The area occupied by sea ice, or the location of the ice edge, is therefore a topic of interest in a range of climate studies, such as the analyses of simulations of past and future climate changes. However, such analyses are hampered by large uncertainties in estimates of the ice-edge location and inconsistencies between different model simulations. This highlights the need for a theoretical framework to provide better dynamical constraints on the location of the ice edge, and on its interaction with the other climate components, notably the oceans. Previous studies using idealised toy models - typically extensions on the classic Energy Balance Model (EBM) of Budyko and Sellers (1969) - have emphasised the sea-ice and atmospheric physics while representing the ocean crudely and neglecting key ocean-ice interactions. However, various studies provide observational and modelling evidence that Ocean Heat Transport (OHT) plays a leading-order role in setting the latitude of the ice-edge in the Arctic Ocean.

Here, the sensitivity of sea-ice extent to prescribed ocean heat flux convergences in existing toy models is presented. Then a novel extension of the classic EBM which includes OHT in a variable-depth mixed layer and prognostic sea-ice thickness is described. This improved toy model can be used to explore the dynamics of the zonally-averaged equilibrium ice-edge latitude. The sensitivity of the ice-edge latitude to model parameters and comparisons to previous idealised models are discussed.

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Indices of deep ocean convection in the subpolar North Atlantic

Deep convection in the subpolar North Atlantic is one of the key components of the Atlantic Meridional Overturning Circulation (AMOC), linking the upper ocean and the deep ocean branches of the AMOC (Buckley & Marshall, 2016). The ongoing warming of the atmosphere (Gulev et al., 2008; Johannessen et al., 2016) and of the subpolar ocean (Alekseev et al., 2001; Yashayaev, 2007), as well as increasing freshwater fluxes to the subpolar seas (Peterson et al., 2006; Dukhovskoy et al., 2016) are expected to decrease the intensity of subpolar convection and may cause its' complete shut-down, affecting the global climate. Difficulty in the direct observations of interannual variations of the deep convection intensity consists in a relatively small size of deep convection cells, only 20-50 km in diameter, combined with variations in locations of development of deep convection (GSP Group, 1990; Johannessen et al, 1991; Kovalevsky 2002; Yashayaev et al, 2007, Bashmachnikov et al, 2018). To overcome these difficulties various proxy indexes of deep convection intensity have been suggested (Meincke et al, 1992; Alekseev et al, 2001; Yashayaev, 2007; Rhein et al, 2011; Falina et al, 2017). However, drawbacks of most of the indices lie either in a relatively weak response of the parameters to significant variations of deep water convection (so that the observed variation are often governed by other ocean processes) or in scars observations of the parameters used.

In the present work we suggest indices that are easy to compute from standard oceanographic observations. Those are based on the water density, on the sea-level anomalies and on the volume of deep water masses formed in the subpolar seas. The intensity of the deep convection is determined as the maximum mixed layer depth in EN4 and in ARMOR gridded data-sets. The suggested indices show high correlations with the derived deep convection intensity during the years, well covered with data. The indices are used for extending the intensity of deep convection back to 1950. During 65 years of data no significant linear trends in the convection intensity in the subpolar seas were obtained. 5-7 year and longer cycles in the convection intensity were detected.

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On the Vertical Velocity Component in the Mesoscale Lofoten Vortex of the Norwegian Sea

For the first time, the concepts of the theory of helical vortices have been applied to the Lofoten vortex of the Norwegian Sea. The estimates for azimuthal and vertical velocities have been obtained from the Massachusetts Institute of Technology general circulation model (MITgcm) for 1992–2012. The columnar vortex model with helical vorticity lines and distributions has been adapted to Scully and Rayleigh vortices. It has been shown that the vortex parameters can be determined simply from mass balance equations. The parameters of the helical vortex simulating the structure of the Lofoten vortex have been found and the radial distributions of azimuthal and vertical velocity components have been constructed. The resulting data can be interesting for an analysis of the three-dimensional structure of mesoscale vortices in the ocean.

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On the evolution of the upper layers in the Canadian Basin: preliminary analyses from IAOOS and ITP data and the global Mercator Ocean system

The Arctic climate has undergone strong modifications over the past decades with a drastic sea ice extent decrease of about 10% per decade. We investigate changes in the Canadian Basin upper ocean layers using in situ data and high-resolution model outputs.

ITP (Ice-Tethered Profiler) 29 and IAOOS (Ice Atmosphere Ocean Observing System) platform 15 deployed respectively in 2008 and 2015 in the north of the Chukchi Plateau followed similar trajectories in the northern boundary of the Beaufort Gyre and the southern part of the Transpolar Drift. A clear freshening is observed down to 200 m (about 1g/kg) in seven years. In addition, the thermocline is 40 m deeper in 2015 than in 2008 and the NSTM (Near surface Temperature Maximum) is stronger in 2015.

Global 1/12° Mercator Ocean operational systems are used to examine the physical mechanisms causing the variations found in the observations. Two operational systems are available : the real time system PSY4V3 from 2008 to 2016 and the reanalysis GLORYS12 spanning the 1993-2015 period. Performance of these two systems is evaluated against the numerous ITP data deployed in the Canadian Basin. Salty surface bias (up to 1g/kg) and a warm bias at about 200 m depth (up to 0.2°C) are present in both PSY4V3 and GLORYS12 systems. However, relative variations and trends are well reproduced. The evaluation of the model performances is on-going and new results are expected.

Both systems indeed reproduce the long-term changes observed in the ITP29 and IAOOS15 data. The Mercator system shows a cold and fresh branch at 200 m depth coming from the center of the Canadian Basin and following the bathymetry up to 84N.

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Modifications of Atlantic inflow along its northern passage towards the Arctic Ocean on seasonal to inter-annual time scales

Understanding variable oceanic fluxes of volume and heat carried by the Atlantic water (AW) into the Arctic Ocean and their impact on ocean-atmosphere-ice interactions, ocean heat content, sea ice changes and propagation of anomalies are key challenges to understand the new, warmer regime of the Arctic Ocean. As the AW progress northwards, its properties are modified by ocean-atmosphere interactions, mixing and lateral exchange. AW temperature drops from 7-10°C at the entrance to the Nordic Seas to 3-3.5°C when it leaves Fram Strait. Warm anomalies reaching the Arctic Ocean can result from smaller heat loss during AW northward passage towards and through Fram Strait, and/or from an increased oceanic advection. During the last two decades the extraordinary warm Atlantic inflow has been reported to progress into the Arctic Ocean, however with strong inter-annual variations. Here we present results from 20 years of annual hydrographic surveys, covering the Atlantic inflow in the eastern Norwegian and Greenland seas, Fram Strait, up to the southern Nansen Basin. Observations from year-round moorings west and north of Svalbard, and from regularly deployed Argo floats are also used to elucidate processes, contributing to AW modifications on its way into the Arctic ocean and resulting changes in the ocean heat content. Long-term large-scale observations reveal new details on spatial structure and temporal evolution of warm anomalies carried into the Arctic Ocean, and their links to ocean-atmosphere-sea ice fluxes and sea ice variability north of Svalbard.

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Atlantic Water transformation along its poleward pathway across the Nordic Seas

The warm and salty Atlantic Water is substantially modified along its poleward transit across the Nordic Seas. The transformed waters, in response to winter heat loss to atmosphere, reach deeper isopycnals and are associated with spiciness which can be informative about the general circulation in the region. In particular, the Lofoten Basin, a reservoir of spicy waters exposed to intense air-sea interactions, plays a crucial role in the transformation of Atlantic Water. Averaged over a seasonal cycle, Atlantic Water releases approximately 80 W m-2 of heat to the atmosphere over a large area, leading to winter mixed layer depths of up to 500m (locally exceeding 1000m in the Lofoten Basin Eddy, a permanent vortex located in the basin center), and substantial water mass transformation. We investigate spiciness injection by winter mixing, by performing an isopycnal analysis using a comprehensive observational dataset covering the 2000-2017. Compared to the Atlantic Water properties at the Svinøy section, representative of the inflowing Atlantic Water, some isopycnals reveal an important warming (up to 1.5C) and salinification (up to 0.2 g kg-1). Key areas for spiciness injection are the western Lofoten Basin, and west of Bear Island. The modified spicy Atlantic Waters coincide with low potential vorticity with strongly density-compensated layers at their base, allowing double-diffusion processes to occur farther downstream toward the Arctic. Despite its limited spatial extent, the Lofoten Basin Eddy exhibits the greatest spiciness injection, as well as the deepest mixed layer and thickest low potential vorticity layer of the Norwegian Seas. The Atlantic Water spiciness at Svinøy shows a downstream correlation in the Lofoten Basin and farther north toward the Arctic with a lag of 1 to 1.5 years.

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Scaling and statistical properties of sea-ice deformation fields from models participating in the FAMOS Sea-Ice Rheology Experiment

Amélie Bouchat, Nils Hutter

As sea-ice models are being run at higher and higher resolution and already reproduce the observed large-scale sea-ice dynamics fairly well, evaluation of current sea-ice rheological models using the smaller-scale sea-ice deformation fields is now possible. Observations from the RADARSAT Geophysical Processor System (RGPS) and in-situ observations show that regions of high deformation (or strain rate) in the Arctic sea ice are localized along well-defined linear kinematic features (LKFs) spanning a few meters to thousands of kilometers. The divergence/convergence of the ice cover along LKFs has a large impact on the sea-ice and ocean states, as it affects the ice production and mass balance, the ocean-atmosphere vertical heat fluxes, and the upper ocean salinity through brine rejection. A realistic representation of LKFs in sea-ice numerical models is therefore essential to adequately model the Arctic climate system.

The FAMOS Sea-Ice Rheology Experiment (SIREx) explores the representation of sea-ice deformation fields in current sea-ice models using a variety of sea-ice rheologies and spatial resolutions. In a first part, the scaling and statistical properties of the simulated deformation fields are analyzed to get a sense for the ability of the different sea-ice rheological models to reproduce the localization of the LKFs in space and in time, as well as to investigate the effects of spatial resolution and other parametrization, to a first order, on the deformation fields. A more detailed analysis of the sea-ice deformation field showing well-defined LKFs is then performed as a second part to evaluate their spatial characteristics (density, length, orientation, intersection angle, etc.) as well as their temporal evolution (see abstract by N. Hutter).

Here, we present preliminary results of the first part of SIREx evaluating the scaling and statistical properties of the modeled sea-ice deformation fields. To ensure that both the Lagrangian RGPS and model deformation fields are calculated in an equivalent framework, we first reconstruct model Lagrangian trajectories for a three-month (JFM) period by advecting buoys starting at the same positions as the RGPS tracked points on 1 January 1997 and 1 January 2008. Deformations are then calculated for different spatial and temporal scales using the line integral formulation for strain rates. The resulting probability density functions (PDFs) for divergence and shear will be presented, as well as selected results of the scaling analysis, and we will discuss the effects of the different rheological models (VP, EVP, MEB,
and EAP).

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Arctic stratification: modeling, stability, and evolution during abrupt changes in sea ice

For the next four years, I will work on Arctic stratification and its response to climate change. The very strong gradient of salinity observed in the Arctic region is most likely maintained by the presence of sea ice and it allows conversely the sea ice to form by isolating the surface from the warm Atlantic water. Sea ice thickness and extent are decreasing at an alarming rate. How did the stratification change in the meantime? Do these changes amplify or regulate the observed trend? The lack of long term observations and the fact that general circulation models do not represent realistically the stratification in this region make this problem difficult to handle. The first part of my project will then consist in tuning models so that they better reproduce the cold halocline. For that purpose I will mainly focus on the parametrization of brine rejection, a key small scale process to understand dense water formation and Arctic stratification. Later, I will try to study the correlation with sea ice changes.

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A new scientific cooperation agreement to ensure Arctic governance

Although the Arctic remains one of the most vulnerable ecosystems around the world , its governance faces today its greatest challenge: "the scientific cooperation", which requires not only the common agreement of the member states, but also two more special things: First, a good lobby among all States members of Arctic Council to arrive at this new stage of integral collective governance. Secondly, the influence of other stakeholders (e.g. indigenous people in the region) to ensure the active scientific cooperation.

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Variability of Arctic Ocean stratification 1980-2016 in three recent ocean reanalyze

This study extends recent efforts by the CLIVAR/GODAE Polar Ocean Reanalysis Intercomparison Project (ORA-IP) to examine climate variability in the Arctic Ocean in an additional three new ocean/sea ice reanalyses: SODA3, ORAS5, and ECCO4r3 with improved resolution, data sets, and forcing fields. The first two analyses span the 37 year period 1980-2016 while the third covers the more recent 24 year period 1992-2015. All three reanalyses have reasonable representations of Atlantic water variability in the Nordic Seas, but differ in their rates of penetration through Fram Strait and the Barents Sea Opening (the coarser reanalysis has reduced Fram Strait transport). All three show a realistic influx of Pacific water through Bering Strait and the haline mixed layer stratification. Interestingly, the storage of freshwater within the Beaufort gyre differs significantly among the three and only one of the reanalyses is able to capture the near-surface temperature maximum of the Canada Basin. At the end of the presentation we briefly review sea ice assimilation efforts in SODA3.

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Internal wave-driven mixing variability in the Beaufort Sea and straits of the Canadian Arctic Archipelago from multi-year mooring data

While ocean mixing is known to be inherently patchy in time, data scarcity in the Arctic Ocean poses significant challenges in our ability to accurately quantify the temporal variability of turbulent mixing in this region. To address this need for broader temporal analyses, we investigate multi-year time series of ocean temperature, salinity, and velocity from mooring records in Nares Strait, Barrow Strait (Canadian Arctic Archipelago), and the Beaufort Sea shelf slope. These moorings, equipped with upward-looking ADCPs that sampled the upper ~100-200 m of the stratified water column, operated continuously from 2003-2006, 1998-2005, and 2003-2004 respectively. In this study, we apply a shear-based finescale parameterization of turbulent dissipation to these records to characterize the time series of wave-driven turbulent dissipation rates, diffusivity rates, and associated turbulent heat fluxes. We assess the variability of these signals on daily, seasonal, and yearly cycles. We further quantify the frequency of significant mixing events and the extent to which they mediate climatological heat fluxes. Finally, we consider the environmental conditions that allow for these high-energy episodic or periodic mixing events to disrupt the typically quiescent nature of the Arctic Ocean interior.

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Arctic Freshwater redistribution and export in coupled climate models: responses to changes in atmospheric circulation

It has been understood for some time that different modes of atmospheric circulation should provoke different responses in the Arctic freshwater reservoir. There are, however, competing processes at play and disagreement remains as to the (time-evolving) effects of different patterns of atmospheric circulation over the Arctic and freshwater redistribution and export.

We find the time-evolving responses in coupled climate models of export through the Fram and Davis Straits, and redistribution within the Arctic basin, to step changes in the strength of the leading modes of sea-level pressure variability over the Arctic. We achieve this by statistically interrogating the control runs of coupled climate models. This method is a computationally efficient alternative to model perturbation experiments, and we present results from the CMIP5 ensemble and Met Office models. We convolve our results with atmospheric reanalysis datasets to construct time-series of freshwater variability over the last century, and assess the role that different modes of atmospheric circulation had in major freshwater changes.

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A new rheological framework for sea ice modelling

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The capability to make reliable numerical predictions of the state of the sea ice cover is becoming essential in the context of (1) estimating the future evolution of both its summer and winter extent in the Arctic and Antarctic, (2) forecasting the opening of shipping routes and (3) inferring the mechanical constraints on offshore structures and ships. This capability requires an accurate representation of sea ice deformation at both regional and global scales. We will present a new mechanical framework that was developed in the view of allowing such an accurate representation of ice deformation and drift in continuum sea ice models.

The model, named Maxwell-Elasto-Brittle, combines the concepts of elastic memory, progressive damage mechanics and relaxation of stresses. A viscous-like relaxation term is added to a linear-elastic constitutive law together with an effective viscosity that evolves with the local level of damage of the material, like its elastic modulus. This framework allows for part of the internal stress to dissipate in large, permanent deformations along the leads once the ice cover is fractured (i.e., damaged) while retaining the memory of elastic deformations over undamaged areas. A healing mechanism representing the refreezing within leads counterbalances the effects of damaging over larger time scales.

The Maxwell-EB model has been implemented in the Lagrangian sea ice model NeXtSIM. Comparisons of year-long simulations of the Arctic sea ice cover and RGPS-derived deformation data have demonstrated that the model successfully reproduces both the extreme strain localization and intermittency of sea ice deformation, with the associated scaling laws. The observed multifractality and space-time coupling between these scaling laws are also represented. The impact of the new rheology will be discussed in terms of the simulated ice-ocean-atmosphere heat exchanges over the Arctic. New developments of the Maxwell-EB model will also be discussed in the context of simulating wave-ice interactions and the transition in mechanical behaviour between the (dense) ice pack and (low concentration) Marginal Ice Zone.

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Recent updates of liquid freshwater and sea ice volume export through Fram Strait

Laure De Steur and Gunnar Spreen (University of Bremen)

The East Greenland Current (EGC) is the largest conveyor of freshwater and sea ice from the Arctic Ocean to the subpolar North Atlantic. Despite wide-spread freshening and major changes in sea ice cover in the Arctic Ocean, the freshwater and sea ice volume export through Fram Strait showed no significant trend up to 2008 (de Steur et al., 2009, Spreen et al., 2009). Since then, year-round salinity and current measurements from the Fram Strait Arctic Outflow Observatory show that the liquid freshwater export in 2011 and 2012 was, at times, twice the long-term mean. These increased freshwater transports were due to a combination of anomalously strong southward velocities and low salinities. Nutrient ratio measurements revealed large inventories of freshwater of Pacific origin in the Fram Strait in the summers of 2011 and 2012 illustrating that a temporary change in Arctic circulation allowed for increased export between 2011 and 2013. Analysis of the long-term sea ice volume export over the monitoring period 1992-2014 shows a declining trend in ice export. Here, we present the first updates of the integral changes in freshwater export - containing both liquid freshwater and sea ice - from the Arctic through Fram Strait.

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SHOM activity in nordic seas and oceanographic cruise of summer 2017

During summer 2017, French research vessel Pourquoi Pas? carried out an oceanographic cruise in the nordic seas for the service hydrographique et oceanographique de la marine (Shom). This campaign is part of a multidisciplinary nordics seas program. The oceanographic component of this program intends to improve oceanographic knowledge of nordic seas and to assess existing operational forecasting capabilities in this new area of interest. A complementary objective of Shom was to verify its capacity for hydrological and current measurements of the ocean in high latitude regions. The planned campaign envisaged collecting in situ data to complete and deepen the characterization of the large-scale circulation of the East coast of Greenland described in the literature and partially well represented in numerical models. The scientific objective of the survey was to estimate the East Greenland current, its structure, its spatial variability, as well as its seasonal variability. Due to adverse sea ice conditions and thus inaccessibility to the planned work area, part of the campaign (long term moorings) has been redirected towards the characterization of the current of Jan Mayen, branch of East Greenland current that forks east north of Jan Mayen's fracture zone and feeds the gyre of Greenland.

This cruise was also an opportunity to evaluate operational or semi operational ice products since besides the scientific objective of the cruise Nordic seas are areas of interest for navigation. As Pourquoi Pas? is not an ice breaker and can only navigate in ice free areas, ice presence was a real preoccupation during the cruise. A monitoring on the evolution of ice conditions was carried out continuously on board from the available operational sea ice products, and an experimentation of neXtSIM sea ice forecasts in real time has been set up with NERSC institute.

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Challenges in modeling ice algae and phytoplankton primary production in the "new" Arctic icescape (talk to the FAMOS School following invitation by Mike Steele)

The Arctic sea-ice regime is changing more rapidly than our capacity to properly model and forecast the ongoing biological changes. We still struggle to define the adequate spatial resolution required to capture the relevant variability of physical, chemical and biological properties or to simulate some of the most important processes linking the mentioned properties, in spite of several decades of modeling efforts. In what concerns sea-ice biogeochemical modeling, studies published over ~30 years show a large diversity of approaches. For example, some authors focused their modeling efforts at the bottom ice, whereas others attempted to simulate the whole ice column. Often, the former argument about the large concentration of biomass at the bottom ice as compared to that at upper levels, visibly influenced by the bottom-ice algal blooms frequently observed in land fast ice. However, the vertical biomass distribution in the pack ice found in the open ocean does not suggest such an overwhelming importance of the bottom communities. Recent empirical and modeling studies emphasize the need of resolving vertically the ice to avoid bias in estimating primary production. Furthermore, there is some evidence of emerging snow infiltration algal communities, resulting from sea-ice flooding due to the negative freeboard provoked by large snow loads that may need to be considered in ongoing modeling efforts. Moreover, sea-ice ridges seem to be an important habitat not resolved by current modelling efforts. The importance of the physical detail, both vertically and horizontally, goes beyond the sea-ice associated processes. Recent studies suggest that the traditional conceptual view of a spring phytoplankton and ice-algal bloom in the Marginal Ice Zone (MIZ) following its progression as a primary production "front", should be replaced by a "network view". This view does not contradict the existence of a frontal primary production zone, but it merely acknowledges the effect of the thinner and more dynamic ice cover in creating a fractal network of refrozen light conduits, deep into the ice pack, along which phytoplankton and ice algal growth rates may be enhanced. There are practical limits for the detail that may be incorporated into coupled physical-biogeochemical models and, in most instances, the only way around is and will be "parameterizing". However, the proper parameterizations require an in-depth dialog between the empirical and the modeling scientists.

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INFLUENCE OF GREENLAND FRESHWATER ON SALINITY OF THE SUBPOLAR NORTH ATLANTIC

Dmitry Dukhovskoy, Andrey Proshutinsky, Jonathan Bamber, Igor Yashayaev

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The cumulative Greenland freshwater (FW) flux anomaly has exceeded 5000 km^3 since the 1990s, which is half of the freshwater volume advected into the North Atlantic during the 1970s Great Salinity Anomaly. The latter event was well observed and recorded in terms of salinity and temperature anomalies at the observational sites in the North Atlantic as the anomaly propagated around the Subpolar Gyre. In contrast to the Great Salinity Anomaly, there is no observational evidence of salinity changes in the North Atlantic that can be directly related to the Greenland FW flux anomaly. The motivation for this study is to investigate the likely origins for an absence of evidence of increased Greenland FW flux. The paper presents results of numerical experiments with a passive tracer released continuously during the simulation at freshwater sources along the Greenland coast. The location and flux rates are derived from a detailed gridded product of Greenland FW fluxes. Results from the model experiments are analyzed to investigate pathways, vertical spreading, and accumulation rate of Greenland freshwater in the subpolar North Atlantic. Predictions of salinity anomalies over the study region related to the Greenland FW flux anomaly are provided based on the numerical simulation and tracer budget analysis. The tracer study suggests the strongest freshening along the Greenland coast (<–0.1). In the interior regions, due to horizontal and vertical mixing the freshening signal is weaker ranging from –0.015 in the upper Labrador Sea to –0.004 in the upper central Greenland Sea. It is concluded that so far, the Greenland freshwater anomaly has had a small impact on salinity in the interior regions.

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Winter ocean heat fluxes under sea ice leads in the Arctic Ocean

Arctic sea ice declines faster than predicted, mainly due to uncertainties from internal climate variability (Jahn et al., 2016) and under-resolved ocean mechanisms (Holloway et al., 2007). The goal of the research is to model the role of under-resolved ocean mechanisms along sea ice leads (Linear Kinematic Features) and their associated ocean heat fluxes. We investigate forcing from brine rejection, Ekman pumping and their combined effects. Results show that both types of forcing lead to fluxes of similar amplitude but that their combined effects are not additive.

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The dominant time scales and spatial patterns of Barents Sea ice variance and retreat

During the last decade reduced winter sea ice growth has led to an accelerated retreat of the Barents Sea ice extent, with 2016 and 2017 being lowest on record. A general dependence of Barents Sea ice cover on the inflow of Atlantic water is well known, and allows for skillful predictability of the ice extent. However, the latter considerations have been concerned with putting one areal number on change without further assessing the dominant temporal- and spatial scales of variance and predictability. Such a detailed assessment is necessary for more practical and informative predictions, and a more mechanistic understanding. In order to examine this issue, the Empirical Orthogonal Function (EOF) method is applied on hydrographic data from the Nordic Sea Atlas, provided by the National Oceanic and Atmospheric Administration (NOAA). This method allows for analysis of both the spatial scale and the time scales responsible for the fluctuation of a variable and the percentage contribution. In addition we applied lagged correlation analysis between the Barents Sea Opening (BSO) hydrographic variables (temperature, salinity, density) and the sea-ice percentance variability of the Barents Sea, in order to detect the most dominant mechanism which contribute to sea-ice variability. Preliminary results show that the dominant sea-ice variability of early winter has high correlation with the temperature and salinity at 200m depth during June at BSO. This correlation shows repeatability every 8-9 years, giving us a new promising tracer for skillful predictability.

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Model study showing the impact of floe size distribution on seasonal fragmentation and melt of Arctic sea ice

Adam Bateson, Daniel Feltham, David Schroeder, Lucia Hosekova, Yevgeny Aksenov, Jeff Ridley

Recent years have seen a rapid reduction in summer Arctic sea ice extent and increase in the seasonal ice cover. Currently in climate models it is assumed that ice floes are uniform in size. This restricts the representation of seasonal ice zone processes within models such as wave-ice interaction. Floe size impacts lateral melt rate, ice rheology and atmosphere-ice-ocean momentum exchange. In this study, the floe size distribution is represented as a truncated power law defined by three key parameters: minimum floe size, maximum floe size, and exponent. This distribution is implemented within the CICE sea ice model coupled to a prognostic ocean mixed layer. We show that the use of a power law distribution can increase the seasonal reduction of the sea ice extent and volume via the albedo feedback mechanism. We also present results suggesting that the role of externally generated waves is severely limited by the rapid attenuation of waves by the sea ice cover. Finally, we explore floe size distribution – mixed layer interactions within a coupled CICE-NEMO model.

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Structure, mixing and variability of the Atlantic Water boundary current around Svalbard

Measurements of ocean currents, stratification and microstructure were made from ships in summer 2015 and 2018, northwest of Svalbard downstream of the Atlantic inflow in Fram Strait in the Arctic Ocean. The process observations are supplemented by one-year long moored instrument records deployed on the southwestern slope of the Yermak Plateau. Processes contributing to the cooling of the warm Atlantic Water boundary current will be discussed. Low-frequency variability and volume transport inferred from the mooring records will be presented.

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The impact on Arctic sea ice of increased ice-ocean drag caused by ocean internal waves

Daniela Flocco, Feltham D.L., Schroeder D., Siahaan A., Aksenov Y.

The phenomenon of dead waters was first observed by Nansen in 1893 when navigating through polar waters; it is caused by the ship's hull inducing internal waves in the ocean that radiate momentum away from the ship, effectively increasing the ocean's drag on the ship. The rough topography of the underside of sea ice also generates internal waves as sea ice drifts over the stratified ocean, increasing the total ice-ocean drag.

A parametrization of the impact of internal waves on momentum transfer at the sea ice-ocean interface has been developed and implemented in a sea ice model (CICE) for the first time. The parameterization comes from a previous study by McPhee, which we have adjusted to account for the presence of keels deeper than the mixed layer depth. The extra ice-ocean drag from internal waves is stronger for shallow mixed layer depth and large density jump at the pycnocline, and is a function of the strength of the stratification beneath the ocean mixed layer and geometry of the ice interface. We consider the contribution to internal wave drag from both ridged and non-ridged ice. The increase of the ice-ocean drag transfer coefficient has consequences on the bottom melt and therefore on the sea ice state.

We have conducted simulations with the CICE model for the Arctic, in which ocean characteristics are calculated from a separate, coupled sea ice-ocean (NEMO-CICE) simulation from 1980 to 2016. We present results demonstrating the regional effect of internal wave drag on emergent Arctic sea ice characteristics such as thickness, motion, and deformation. We also present preliminary results from a coupled sea ice-ocean model (NEMO-CICE) where the internal wave drag has been implemented.

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Representation of the shelf areas in the global ocean model: key study, questions and perspectives

The East Siberian Arctic Shelf (ESAS), consisting of the Laptev, East Siberian and Chukchi Seas, represents the shallowest and broadest shelf region of the entire World Ocean. It occupies a little more than 20% of the total area covered by the Arctic Ocean (AO) and represents a critical physical and biochemical gateway for exchange between AO and terrestrial zone with complex oceanographic and biogeochemical regime influenced by both seawaterof Pacific and Atlantic origins. The is a growing need for better quality estimations of circulation and dynamics on the shelf to answer major present and future scientific, ecosystem and societal issues, because of changing climate. It is a complex task as soon as the ESAS represents wide area with variety of regimes and there is still substantial uncertainty in their role and feedbacks with the wider climate system. Making progress on this is largely dependent on the accurate reproducing of the physical environment in the coupled coastal-open ocean system. We would like to propose modeling system that will help to answer questions on the ESAS observed and future trends and dynamics features across time and space scales tracing the signal through the system Estuaries-ESAS-AO in both upscaling and downscaling directions. To reach mentioned goals, we built a coastal branch of the finite volume version of the global sea ice-ocean model FESOM (Danilov et al., 2004; Danilov, 2012; Wang et al., 2014). FESOM is the first model worldwide that provides multi-resolution functionality to large-scale ocean modeling, allowing to bridge the gap between scales. This unique feature is crucial for high efficient coupling, as soon as the exchange zone can be resolved similarly (with the same resolution) by the global and local solutions. Additional strong side of the elaboration of the coastal branch for the existing global model is a possibility to organize flux treatment in a same manner, increasing efficiency of coupling.

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Evolution of snow and sea-ice during winter: comparisons between observations and numerical simulations document the impact of the initial salinity profile.

S. Gani, N. Sennéchael, C. Provost, J. Sirven

SIMBA data collected north of the Svalbard during winter 2015 during the Norway-led N_ICE project (http://www.npolar.no/en/projects/n-ice2015.html) document the temperature and the thickness of snow and sea-ice as well as various physical quantities in ocean and atmosphere. Such data permit to report how the different media interact and to quantify the processes that come into play (e.g. Provost et al. 2017, Koenig et al., 2016). These results suggest that 1D models of snow and sea-ice, which require a precise knowledge of the flux at the interfaces air-snow and ice-ocean, could be efficiently used to improve our understanding of the mechanisms acting in the ice. We present results obtained from simulations made with the LIM1D model (Vancoppenolle et al., 2010). A comparison with the observations shows that the model is able to reproduce the evolution of temperature and thickness in the ice. The influence of the salinity on the evolution of the simulations is investigated. A better estimation of the latter can improve significantly the quality of the simulations.

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Net thermodynamical sea ice growth from NAOSIM hindcasts

As ice volume and ice export are decreasing, net thermodynamic growth must become negative in the Arctic. We investigate the seasonal cycle and the spatial distribution of Arctic sea ice melt and growth. A novell tracer is used to quantify the impact on Arctic and subarctic ocean salinity

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Ocean Modelling in proximity to Fjords of Marine Terminating Glaciers of the Greenland Ice Sheet

Marine terminating glaciers are one of the most influential components of the Greenland Ice Sheet for releasing freshwater into the ocean. As previous studies have suggested, the vertical distribution of glacial meltwater can be important for the renewal of warm modified Atlantic Water, and therefore plays a role in the maintenance or eradication of these marine terminating glaciers. We use a regional eddy-permitting coupled ocean-sea-ice general circulation model to determine the impacts of Greenland meltwater and icebergs into the ocean. We set up a suite of experiments in a 1/4 degree Arctic and Northern Hemisphere Atlantic configuration of NEMO v3.6, forced with realistic estimates of Greenland's meltwater. This study will assess the importance of meltwater distribution in ocean models for the renewal of warm water back onto the Greenland Shelf. Preliminary work will be shown on how we plan to examine small-scale features in the fjords with known large marine terminating glaciers by using an adaptive mesh refinement package AGRIF. This allows a regional ocean model to resolve fjords of marine terminating glaciers at a resolution of less than 1 km.

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Modeling water exchange between the East Siberian Arctic Shelf and the Arctic basin

Water exchange between the East Siberian Arctic Shelf and the Arctic basin is investigated by using a coupled ice-ocean Arctic model forced by atmospheric reanalysis dataset. In order to numerically track the spreading of the Siberian Rivers waters we used the method of Lagrangian particles. The pathways of the passive tracers injected in an amount corresponding to the observed monthly mean rivers runoff were investigated during the different modes of atmospheric circulation.

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Observations of Atlantic water variability during the AREX summer campaigns: impact on sea ice concentration

Systematically shrinking and thinning sea ice cover of the Arctic Ocean is both an effect and a cause of accelerated climate changes in the Arctic region observed in the last decades. Oceanic water masses from the North Atlantic flow towards the Arctic Ocean in the eastern part of Fram Strait, carried by the West Spitsbergen Current. Fram Strait, as well as the north of Svalbard area, play a key role in controlling the amount of oceanic heat supplied to the Arctic Ocean, and are the place of dynamic interaction between the ocean and sea ice. The north of Svalbard area is one of the regions where the substantial changes in sea ice concentrations are observed both in summer and in winter. Hydrographic data from vertical CTD profiles were collected during annual summer expeditions of the research vessel "Oceania", conducted in Fram Strait and the southern part of the Nansen Basin over the past two decades. The measurement strategy of the original research program AREX, which consists of the performance of cross-sections perpendicular to the presumed direction of the West Spitsbergen Current, allowed to observe changes in the properties and transport of the Atlantic Water carried to the Arctic Ocean. The observed increase in the Atlantic Water temperature was the dominant cause of the decline in the Arctic sea ice concentration in the studied area, especially during the winter. The primary objective of the work is to analyse and present the results of relationships between temperature, volume and heat transport by the Atlantic Water layer along with the West Spitsbergen Current in the context of changes in the concentration and extent of sea ice occurring in two regions: the north of Svalbard and central part of the Fram Strait.

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Dynamical sequences of ocean, atmosphere, and sea ice processes during an abrupt climate transition in the Marine Isotope Stage 3

Marine Isotope Stage 3 (MIS3; ~ 60 ka to 30 ka BP) was puntuated by abrupt climate transitions between colder stadial and warmer interstadial climate conditions. The fluctuations are known as Dansgaard–Oeschger (D-O) events which are featured by a rapid warming from stadial to interstadial in a few decades as recorded by the Greenland ice cores.

In this work, using a state-of-the-art climate model, the Norwegian Earth System Model (NorESM) that is configured for paleoclimate simulations (two-degree atmosphere and one-degree ocean), we investigate the transient response of the climate system from a stadial to interstadial climate state. The stadial state is realised by applying freshwater flux to a MIS3 control simulation. With support from a high-resolution marine sediment core in the Nordic Seas (MD99-2284), we addressed the key role played by sea ice in modulating the Greenland temperature change during the transition, and idendified the sequences of changes in the ocean and its interactions with sea ice and the atmosphere. We found that in agreement with proxy reconstructions, changes in the ocean (e.g. AMOC and heat/salt transport) precede deep convections and melting of sea ice in the Nordic Seas, with the latter process concurrent with the increase of Greenland temperature.

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Propagation of subsurface Atlantic Water into the Canadian Arctic and its potential to trigger retreat of outlet glaciers

The rapid retreat and acceleration of marine-terminating outlet glaciers in west Greenland since the late 1990s has been linked to the propagation of a warm subsurface Atlantic Water anomaly along the Greenland coast. However, it is unknown how far north the Atlantic Water anomaly penetrated and if it crossed Baffin Bay to enter the Canadian Arctic Archipelago (CAA). The CAA contains the largest glaciated area (~150,000 km2) outside of Greenland and Antarctica, with approximately one third of the area drained by marine-terminating outlet glaciers, meaning changes in ocean conditions at their termini could have broad implications for glacier dynamics in the region. Utilizing archived ocean observations from multiple sources and output from the Nucleus for European Modelling of the Ocean (NEMO) ocean circulation model we examine the historical distribution of Irminger Water (IW; water with a salinity >34.1 and a temperature maximum between 200-500 m depth) in Baffin Bay and the CAA, and analyze recent changes in its heat content and extent. Historical ocean observations collected between 1916 and 2017 show the average temperature of the IW layer has varied over time, but was marked by a substantial warming (by >1 oC) in some straits of the CAA after the year 2000. Modelled ocean properties between 1970 to 2012 show a similar warming of IW in Baffin Bay, with further penetration into the CAA after 2000. We examine the circulation pathways of IW in northern Baffin Bay and the CAA, bathymetric constraints on its ability to contact glacier termini, and discuss the potential for IW to trigger retreat of outlet glaciers in Canada.

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A deep learning based predictions of Arctic sea ice concentration using satellite and reanalysis data.

The Arctic sea ice concentration (SIC) is one of the main factors to understand the change of Arctic environment. The prediction of the Arctic SIC has been studied by several approaches such as numerical, statistical models and data assimilation. The change of Arctic SIC is highly related to the atmospheric, oceanic and climate environments. Thus it is important to find the relationships between SIC and other environmental factors. However, due to the complicated simultaneous interactions, it is hard to figure out their physical relationship. This is the motivation of this study: prediction of SIC using the only dataset without complicated interactions between several environmental factors. In this study, data from satellites and reanalysis models were used to predict Arctic SIC using states-in-arts deep learning approaches. The deep learning-based model predicts SIC only from the given data, so no assumption or equations are needed. It shows improved performances compared with several models such as machine learning and statistical models.

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High resolution sea ice modeling during Year of Polar Prediction

July – September 2018 is one of three scheduled special observation periods for the Year of Polar Prediction (YOPP). Planned observations include daily radiosondes from many shipboard and land based locations as well as multiple airborne ice observation transects. In addition, the Swedish icebreaker Oden will set up a drifting ice camp that is planned to drift through the Fram Strait. The U.S. Naval Research Laboratory is providing support to YOPP by making model output available from the Global Ocean Forecast System 3.1 (GOFS 3.1) and Navy Earth System Model (NESM). In conjunction with this special observation period we have set up a high resolution (1 km) regional CICE sea ice model in the Fram Strait and north of Greenland forced with a nested 27/9/3 km U.S. Navy Coupled Ocean Atmosphere Mesoscale System (COAMPS) atmospheric model. CICE boundary conditions and ocean forcing are obtained by GOFS 3.1. In this presentation the performance of the high resolution model compared to observations will be shown, as well as the influence of model resolution as compared with GOFS and NESM.

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A Climate System Model Targeted for the Study of High Latitude Processes

We document the configuration, tuning and evaluation of the initial version of a climate system model specifically intended for the study of high latitude processes, establishing a context from which to improve the representation of such processes.

Starting from CESM.1, the updated version of the model includes changes to the atmospheric model to improve aerosol transport to high northern latitudes and to reduce shortwave cloud bias over the Southern Ocean. Marine biogeochemistry has been extended, with changes to ocean BGC and inclusion of sea ice BGC supporting the capability of having cloud nucleation dependent on marine emissions of aerosol precursors, and providing an improved context in which to study the rapidly changing climate of the high latitudes.

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Simulating Arctic climate change and the impact on lower latitudes in high resolution (4.5 km in the Arctic) with AWI-CM

The fully coupled climate model AWI-CM is run on two different ocean grids to investigate the impact of horizontal resolution on the simulated Arctic Ocean circulation, and Arctic-Atlantic as well as Arctic Pacific linkages. The ocean-sea ice component runs on an unstructured grid, the low-resolution version has a grid size of about 24 km in the Arctic Ocean, while the high-resolution grid has a grid size of about 4.5 km resolution in the Arctic Ocean. The high-resolution grid has already been tested in uncoupled runs with CORE-II forcing, where is showed improved representation of Atlantic Water circulation and associated heat content in the Arctic. Now, the impact of the higher resolution will be assessed in the coupled set-up and on longer time scales (150 years).

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Understanding the Space-Time Variability and Predictability of Arctic Sea Ice Attributes - A Statistical Approach

Recent decline of Arctic sea ice extent, exacerbated by anthropogenic warming has increased the prospect of an ice free arctic and has gained much attention in the literature. The retreat of sea ice offers opportunities (shorter shipping lanes, tourism, etc.) and also geopolitical challenges among the Arctic Nations and near Arctic observers. Planning for these opportunities and challenges requires understanding of the space-time variability of sea ice attributes (extent, concentration, ice-melt date etc.) along with skillful long lead predictability on seasonal time scales. Current physical models have proven to lack skill in long lead predictions beyond 3-month lead times, and large-scale statistical modeling has been largely unexplored. These needs and gaps motivate this research. Data compiled from the National Snow and Ice Data Center (NSIDC) and the National Aeronautics and Space Administration (NASA) in the form of dates of snow cover melt, sea ice melt onset, sea ice retreat, and MERRA2 Reanalysis are used to analyze atmospheric, oceanic, and terrestrial teleconnections to sea ice attributes and to develop predictive models at varying lead times. Principal Component Analysis and Self-Organizing Maps are used to diagnose the space-time variability and also determine the best set of predictors by analyzing patterns in ice melt in relation to snow melt and climate variables such as sea surface temperatures, sea level pressure, and surface air temperature. With the best set of predictors, Canonical Correlation Analysis is used and validated at varying lead times to create predictive models that capture the greatest variability in sea ice. Results from this research will advance the knowledge of sea ice variability and the skillful predictions will be of immense use to various sectors – defense, tourism, shipping etc. for efficient planning of resources.

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Comparing deformation features of sea ice models contributing to the FAMOS Sea-Ice Rheology Experiment

Nils Hutter, Amélie Bouchat

Leads and pressure ridges crossing the Arctic sea ice cover are evidence of the constant deformation of sea ice driven by winds, ocean currents, and interaction with coastlines. With increasing resolution of classical (viscous-plastic) sea ice models, or using new rheological frameworks (e.g. Maxwell elasto-brittle), sea-ice models start to resolve this small-scale deformation. So far, the evaluation of modelled deformation features is limited to scaling properties of sea-ice deformation and other measures like lead area density. These provide specific information extracted from a continuous fields like sea ice concentration but lack a comprehensive description of deformation features.

Here, we present a new way of comparison by detecting individual deformation features in the sea ice cover with an object-based detection algorithm. Combining this information with the sea ice drift fields used to derive the deformation fields, the deformation features are tracked in time. Deformation features are extracted for all sea-ice models contributing to the FAMOS Sea-Ice Rheology Experiment with spatial resolution higher than 10km for winter month (JFM) in 1997 and 2008. The modelled deformation features are compared with respect to spatial characteristics (density, length, orientation, intersection angle, curvature) as well as the temporal evolution against a LKF data-set generated by the same algorithm from RGPS data. In doing so, we study the influence of different rheologies (VP, EVP, MEB, and EAP), different grid resolutions, and other parameterisations on the representation of leads and pressure ridges in the simulations.

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Sea ice deformation: datasets acrross differnet temporal and spatial scales, and its importance for the sea ice mass balance

In the changing Arctic where the sea ice is getting thinner and at the same time moving faster, also ice deformation processes are increasing. The magnitude of deformation rates are however hard to compare as they depend on spatial and temporal scales of the measurements. Here we present results from the N-ICE2015, an expedition to the ice covered region north of Svalbard in the first half of 2015. The deformation rates we measured on N-ICE2015 by buoy arrays were one of the highest ever recorded in the Arctic at similar scales (10-100 km at 1-3 hour interval). We also measured the deformation at shorter scales (100 m-5 km at 10 min interval) from the ship radar images. To bridge between the spatial scales we supplemented these two deformation estimates by deformation rates from satellite remote sensing (SAR) images based on sea ice drift (1-500 km at 1 day interval). These three datasets allow us to quantify the scaling law relationships over a large range of spatial and temporal scales, and help us to estimate the extent and consequences of the major deformation events observed. During N-ICE2015 the sea ice in the Atlantic sector of the Arctic was impacted by several powerful storms. These storms penetrated deep into the pack ice and permanently damaged the ice. We will use the deformation rates obtained from SAR sea ice drift to estimate the importance of the ice age and distance to the ice edge for deformation and healing processes of sea ice.

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Beaufort Gyre: Advective Pathways from Lagrangian back-tracking

Using a Lagrangian particle tracking technique in conjunction with the 1/12° resolution NEMO model, we characterise advective pathways leading to the Beaufort Gyre. Lagrangian 'particles' are released in the Beaufort Gyre region at varying depths, and ARIANE tracking software is run backwards in time to investigate their source: Mackenzie River, Pacific Ocean, or Eurasian Rivers. Using Empirical Orthogonal Function (EOF) analysis, we characterize the variability of pathways followed by each source, and present evidence of a "waiting room" region in which particles accumulate before flowing into the gyre. The link between this waiting room and the Arctic Ocean Oscillation is discussed. Additionally, we note the unexpected result that large numbers of particles initialised at the surface in the Beaufort Gyre are backtracked to the Pacific Ocean, despite the Pacific layer being ostensibly below this. Possible explanations for this surprising behaviour are discussed.

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Assimilating sea ice in an Earth system model and impacts for climate prediction

We present the added value of assimilating sea ice concentration (SIC) within the Norwegian Climate prediction Model that combines the fully coupled Norwegian Earth system model (NorESM) with an ensemble Kalman filter data assimilation method. In an idealised twin experiment we identify the optimal implementation of SIC assimilation in NorESM that is using the multi-category CICE model. It is found that: 1) updating SIC of each individual category yields large improvements of SIC and ice thickness (SIT) without introducing a drift 2) joint coupled update of ocean and sea ice enhances the performance of the ocean and the sea ice component. This setting is applied in a real framework in combination with assimilating SST and sub-surface hydrographic data for the period 1980-2010 and compared to the version of the system without SIC assimilation. SIC assimilation greatly reduces the SIT error compared to an independent data set. The seasonal prediction of sea ice extent is greatly enhanced for all sub-regions of the Arctic and predominantly beats persistence. We will discuss the seasonality in the performance in different Arctic regions and thus identify regions and seasons in which 1) the variability is mostly driven by the ocean and thus already successfully constrained by ocean assimilation, and 2) in which assimilating SIC enhances the forecast skill

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Warm water subduction in the Canada Basin in December 2016

The shallow Chukchi Sea is a gateway of the Arctic Ocean for the Pacific Water, which supplies heat, freshwater, nutrients and carbon from the Pacific Ocean to the Arctic. While a substantial portion of Pacific Water flows through Barrow Canyon, located at the shelf break in the northeast corner of the Chukchi Sea, little is known about the pathways of the water after passing the canyon in winter. We present vertical profiles of wintertime hydrography in the Canada Basin obtained by the McLane Moored Profiler (MMP), an autonomous profiling instrument, and its link to the upstream Barrow Canyon hydrography.

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Water masses of the Barents Sea: Modification and further spreading

A high resolution model is used to trace and quantify the modification of Atlantic Water within the Barents Sea and the pathways of Barents Sea water into the Arctic Ocean.

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The role of wind stress in the Arctic and North Atlantic freshwater covariability

Observations from recent decades show significant salinity anomalies in the Arctic and the subpolar North Atlantic oceans. The evolution of their freshwater budgets has been the focus of many studies, most of which suggest a link between them. However, the nature and the significance of this link is still disputed, as are the driving forces behind it.
Our aim was to perform a series of numerical simulations of the freshwater system of the Arctic and the subpolar North Atlantic oceans and to assess the role of wind stress in shaping it. For this we used the Max Planck Institute Earth System Model and ran model experiments in a partially coupled configuration applying the so called Modini-method with prescribed wind forcing. We constructed idealized scenarios of wind stress forcing associated with large-scale patterns of observed atmospheric variability. We present our results from scenarios representing prolonged positive or negative states of the AO/NAO. We also analyze the response to a sudden change from one state to another with particular focus on the Arctic and the North Atlantic freshwater reservoirs and the fluxes between them. This enables us to simulate the high freshwater content observed in the Beaufort Gyre concurrent with an unusually persistent anticyclonic wind pattern in the Arctic in recent years, and to study the effect of large-scale circulation shifts on Arctic freshwater export and thus salinity anomalies in the subpolar North Atlantic Ocean.

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Satellite observations of eddies in the Chukchi and Beaufort Seas

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Here we present the results of satellite observations of eddies in the Chukchi and Beaufort Seas. The study is based on analysis of high-resolution Envisat and Sentinel-1 synthetic aperture radar (SAR) images acquired during summer months of 2007, 2011, and 2016-2017; and complimented by multi-mission satellite altimetry data from May 1993 to December 2016. Detailed maps of eddy observational frequency, their spatial and dynamic properties are presented and compared with results of high-resolution MITgcm model.

This work is supported by RFBR grant 16-29-02106 mol_a_dk, RSF grant No. 18-77-00082, FASO Russia project No. 0827-2014-0011, Fulbright Visiting Scholar Program and Davidow Discovery Fund.

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Study of seasonal and interannual variability of thermodynamic characteristics of the East Siberian Arctic shelf water based on numerical modeling

Based on the analysis of data from a series of numerical experiments, it is proposed to identify the main physical mechanisms responsible for the formation of the water state and the sea ice in the shelf seas of the Eastern Arctic. Estimations of the influence of the atmospheric variability on the overall state of the shelf zone, the fast ice formation, the processes of formation and melting of the sea ice, its drift and water circulation in the surface layer were obtained based on the modified ocean-ice numerical model developed in the ICMMG SB RAS using atmospheric data from reanalysis. The effect of incoming fresh river water on the general circulation of the shelf seas was estimated.

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Assessing Artic Ocean heat content in global climate models

Climate models are presently being used to understand, predict and project climate changes on a range of time scales. However, there are large biases in these models, and in particular for the Arctic Ocean. Assessing climate models against observations is essential in order to improve the models and understand their predictive capacity. We will therefore investigate how well the next generation of global climate models can simulate decadal changes in the Arctic Ocean heat content. A suite of climate models will be collected and compared with Ocean Reanalyses (ORAs) data for the period 1993-2010. ORAs employ a variety of ocean general circulation models and data assimilation schemes to synthesize a diverse network of available ocean observations in order to arrive at a dynamically consistent estimate of the historical ocean state. The Polar Ocean Reanalyses Intercomparison Project is currently assessing the Arctic Ocean heat content in 10 ORAs (Uotila et al., 2018), and we will use ORAs to benchmark the skill of the climate models. The next generation of climate models is expected to be ready in 2018, and simulations will be available through the Coupled Model Intercomparison Project Phase 6 (CMIP6). The aim is that this analysis of CMIP6 model results will provide a better understanding of the uncertainties and variability related to the Arctic Ocean heat content.

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Emergence of Climate Change Signals in Arctic Freshwater Fluxes

Because Arctic freshwater budget terms can have implications for global climate and there are a number of uncertainties associated with their projected values, it is important to be able to identify potential areas of focus for future research monitoring and measurement efforts. In this project, the CESM ensemble suite is used to explore changes in Arctic freshwater fluxes between the 20th and 21st centuries and to investigate the separation of climate changes due to internal variability and to external forcing. The analysis examines how simulated Arctic freshwater flux terms in externally forced scenarios compare with pre-industrial control run values that are used to represent internal variability. Simulated freshwater flux variables with large changes outside defined internal variability ranges are identified, and potential freshwater variable climate regime shifts are discussed as potential focus areas for future research.

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Refining Exchanges Across Fram Strait: A High-resolution Model Study

As the Arctic has been experiencing an unprecedented warming, sea ice loss has been accelerated and linked to the shifts in atmospheric and oceanic circulations. These pan-Arctic trends are generally revealed in global climate model (GCM) simulations. However, such simulations are often limited in representing the accelerating rate of Arctic change, possibly due to unresolved (or under-resolved) physical processes and feedbacks, especially critical in polar regions. For example, those processes may include transport, distribution and accumulation of heat in the upper ocean and its interaction with the sea ice as well as the atmosphere. Such uncertainties of GCMs in representing Arctic processes possibly stem from a combination of coarse horizontal and vertical resolutions, inadequate parameterizations, or under-represented processes in high-latitude waters, and they affect model skill in representing and predicting polar climate.

In order to better understand and to evaluate sensitivities of such GCM limitations to simulating variability and trends in the Arctic Ocean, a series of numerical experiments are performed using the high-resolution Regional Arctic System Model (RASM). RASM consists of the atmosphere, ocean, sea ice, land hydrology and river routing components, coupled through the Community Earth System Model flux coupler. Fully coupled and forced sea ice-ocean RASM configurations are used at varying spatial resolution and parameter space. The ocean and sea ice components are configured at the horizontal resolution of 1/12 degree (~9km) or 1/48 degree (~2.4 km) with 45 or 60 vertical levels. We focus on Fram Strait as the main gateway for the oceanic volume/property fluxes in/out and ice export out of the Arctic Ocean and their sensitivity to altered horizontal and vertical resolution as well as to parameterizations of air-ice-ocean coupling. We evaluate model results against moored hydrographic observations and satellite-derived measurements around the Fram Strait region. Model performance is quantified using different skill metrics to guide improved GCM simulations of such exchanges across Fram Strait. Our analyses suggest that both surface momentum coupling and model resolution influence the oceanic and sea ice transports across Fram Strait due to the variability of upper ocean thermohaline structure and flows.

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The impact of tides on simulated landfast ice in a pan-Arctic ice-ocean model

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Most sea ice models poorly simulate the landfast ice cover. This is often due to an underestimation of ice arching and the lack of a parameterization to represent the grounding of pressure ridges in shallow water. Recent work has shown that a modified sea ice rheology and the addition of a grounding scheme notably improve the simulation of landfast ice in regions such as the East Siberian Sea, the Laptev Sea, the Kara Sea and along the Alaskan coast. However, these numerical experiments indicate there is an overestimation of the extent of landfast ice in regions of strong tides such as the Gulf of Boothia, Prince Regent Inlet and Lancaster Sound. In this study, pan-Arctic simulations are conducted with an ice-ocean (CICE-NEMO) model with a modified rheology and a grounding scheme. We study the impact of tides on the simulated landfast ice cover. Results show that tides clearly decrease the extent of landfast ice in some tidally active regions. Thermodynamics and changes in grounding cannot explain the lower landfast ice area due to tides. We rather demonstrate that this decrease in the landfast ice extent is dynamically driven by the increase of the ocean-ice stress due to the tides.

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Importance of stratification in modelling shift towards a new Arctic

The Arctic Ocean is cold, stratified and sea-ice covered due to presence of a thin 'Arctic layer' of cold and fresh water that hinders the heat in the deep 'Atlantic layer' from reaching the surface, thereby enabling sea ice to cover the ocean. It is crucial that the Arctic layer is fresher than the Atlantic layer, as this sets up a density difference that effectively limits the vertical mixing between the layers and reduces the upward fluxes of heat and salt. The freshwater content of the Arctic Ocean has been projected to increase due to increased river runoff and precipitation, but observations show a two-sided development of the Arctic Ocean: The freshwater content is increasing in the Amerasian Basin, while the Eurasian Basin is losing freshwater and becoming weakly stratified. At the same time, the Eurasian Basin experiences the greatest lower atmospheric warming and greatest reduction in sea ice cover, and this development is further enhanced in the northern Barents and Kara Seas.

Here, we propose a link between changes in freshwater, ocean stratification, sea ice cover and lower atmospheric warming based on an extensive set of hydrographic observations in the northern Barents Sea from 1970 to 2016. A sharp increase in ocean temperature and salinity is apparent from the mid-2000s, which we show can be linked to a recent decline in sea-ice import and a corresponding loss in freshwater, leading to weakened ocean stratification, enhanced vertical mixing and increased upward fluxes of heat and salt. This resulted in a dramatically warm Arctic layer, that after 2010 had temperatures up to 6σ above the 1970–1999-mean. The additional heat in the upper ocean is likely lost to the atmosphere during winter and may explain the enhanced atmospheric warming and loss of winter sea ice cover in this region.

Overall, this implies that ocean stratification is a highly dynamical variable in the Arctic climate, and a key parameter when modelling the shift towards a weakly stratified, seasonally ice-covered eastern Arctic. The upward salt flux involves a positive feedback that further weakens the stratification, and the vertical processes mentioned here may therefore become increasingly important as the stratification weakens in the development towards a *new Arctic*.

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Can we detect subsurface eddies in the ice-covered Arctic from space?

Mesoscale eddies are ubiquitous in the ocean. In the Arctic Basin, which is characterized by a small Rossby deformation radius, subsurface eddies have the potential to impact the stability of the sea ice cover, as they are able to disturb the strong stratification or to carry significant amount of heat and freshwater. However, the dynamical and thermodynamical processes at play in these interactions are still poorly pinned down. One challenge arises from the presence of sea ice that prevents the detection of small eddies in satellite observations of sea surface height or temperature as it is routinely done in other oceans. Major progress in our understanding of the Arctic mesoscale activity has however been achieved recently, as observations of high temporal and spatial resolution temperature and salinity profiles from Ice-Tethered Profilers (ITP) have been proven to be very efficient in providing an extensive description of eddy characteristics. Here we provide evidence, for the first time, that a signature of some subsurface eddies observed by ITP can be found in satellite observations of sea ice concentration. We combine ITP observations with satellite sea ice and drift observations to extensively describe a few cases. It allows us to quantify some of the important processes involved in the interactions between ocean eddies and sea ice, and to evaluate the relative contribution of dynamical and thermodynamical processes

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Modeling the Arctic colored dissolved organic matter (CDOM) and phytoplankton diversity in/with support to/from satellite retrievals

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In our study we focus on improving our understanding of possible interactions between the open water, sea ice and surface ocean biogeochemistry under recently observed sea ice decline in the Arctic. In particular, we consider changes in phytoplankton functional types (PFTs) based on long-term time series of satellite retrievals, investigate plausibility of existing satellite algorithm for deriving colored dissolved organic matter (CDOM) and complement with coupled sea-ice - ocean - biogeochemistry modeling. The CDOM and phytoplankton dynamics as well as phytoplankton diversity in response to Arctic Amplification are simulated with the DARWIN biogeochemical model (Dutkiewicz et. al. 2015) coupled to the Massachusetts Institute of Technology general circulation model (MITgcm, MITgcm Group, 2012). The biogeochemical module is augmented with an optical/radiative transfer model (RTM) that allows us to consider explicitly phytoplankton and CDOM as oceanic optical constituents and, therefore, to investigate possible feedbacks between ocean – oceanic biota – sea ice – atmosphere and evaluate satellite ocean color products and algorithms.

Dutkiewicz, S., Hickman, A. E., Jahn, O., Gregg, W. W., C. B. Mouw, C. B., and M. J. Follows (2015) Capturing optically important constituents and properties in a marine biogeochemical and ecosystem model Biogeosciences, 12, 4447–4481.

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Atmospheric correction for sea ice concentration retrieval using passive microwave satellite observations

An improved sea ice concentration (SIC) retrieval algorithm named ASI2 that uses weather corrected polarization difference (PD) of brightness temperatures (TBs) at 89 GHz measured by AMSR-E/2 is developed. Effects of wind, total water vapor, liquid water path, and surface temperature on the TBs are evaluated through a radiative transfer model. The weather effects are corrected by simulating changes in TBs caused by the atmospheric water absorption/emission and wind roughened ocean surface. Two types of data are used as atmospheric profiles in the correction, namely the atmospheric re-analysis and the optimal estimation data. The correction based on optimal estimation data more effectively reduces the error in sea ice concentration retrieval induced by atmospheric influence, resulting in less spurious ice over open ocean and more homogeneous ice concentration in the center of Arctic. Compared to the original ASI algorithm, ASI2 allows retrieval of low ice concentration and resolves a more exact ice concentration gradient across the ice edge.

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Evaluation of cascading water formation from NEMO-shelf model simulations.

Cascading is thought to be one of the major players in shelf-ocean interaction in the Arctic Ocean and to contribute to carbon export from continental shelves to the open ocean. Hence, it might influence the long-term sequestration of the carbon drawn-down from the atmosphere by biological production in shelf seas, with consequences for global climate (Huthnance et al., 2009, Holt et al., 2009). However because it is an episodic process, happening in a winter time, it is difficult to observe.

We use NEMO-shelf Arctic Ocean model to evaluate cross-shelf exchange and dense water fluxes in the Arctic Ocean; and identify the role of sea ice, surface and bottom Ekman drains on cascading process. We analyze outputs of three 30 years long runs, which differ by inclusion or not the tidal forcing, and different river runoff representation. We identify the locations of preconditioning to cascading (as the area, where the mixed layer depth reaches the bottom of the shelf and salinity is higher compared with salinity of ambient waters in the deeper ocean) and pathways of propagation of cascading waters.

The most strong cascades across isobaths 300m are found in the east Davis Strait, the Irminger and Barents Seas, with the 25 year mean mass fluxes above 3m2s-1 (3 SV/1000km) and isolated, but very intensive plume in the North-West shelf break of the Greenland Sea (above 5 m2s-1).

In the deep Arctic, surface Ekman drain is a dominant process responsible for the shelf-ocean exchange with 25 years mean positive, offshore fluxes 0.6-0.7Sv (across isobaths 300m). With more seasonal ice surface Ekman fluxes grow with the rate of 0.014 Sv/year, presumably due to dominating anticyclonic wind circulation during last decade. 25 years mean cascading flux is about half of that (0.35Sv) and grows with time with the rate 0.004Sv/year. This support hypothesis (Ivanov et al, 2015) that with growth of seasonal ice cascading processes will be increased.

Tides support the formation of cascades in the deep Arctic, while increasing river runoff and Greenland melting suppress this process. Variability of cascading downward fluxes is strong, with standard deviations several times exceeding mean values in some locations.

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The Arctic Climate Response Function Project

We report on progress in a coordinated set of Arctic modelling experiments which study how the Arctic responds to changes in external forcing. We explore the transient response of freshwater content (FWC) of the Beaufort Gyre to an abrupt “step” change in the wind field across a number of Arctic models. The response is rationalized in terms of a simple analytical model of the interplay of the inflation of FWC through the action of the wind, and deflationary tendencies due to the ice-ocean governor, mesoscale eddy processes and diapycnal processes. We also review ongoing activities that explore the response of fresh water and heat export through Fram Strait to a wind perturbation in the Greenland Sea.

The Ice-Ocean stress governor: ice-ocean stress feedback limits Beaufort Gyre spin up

Gianluca Meneghello, John Marshall, Jean-Michel Campin, Edward Doddridge, Mary-Louise Timmermans)

The Beaufort Gyre is a key circulation system of the Arctic Ocean and the main reservoir of freshwater within it. Storage and release of its freshwater not only has significant implication for the fate of Arctic sea ice cover, but also to the climate of the North Atlantic and globally. We present a theoretical interpretation of a mechanism that is fundamental to the dynamics of the Arctic and its ability to store fresh water, namely the "ice-ocean stress governor". Wind blows over the ice and the ice drags the ocean along with it. But as the gyre spins up, surface currents catch the ice up and effectively turn off the Ekman pumping. This governor sets the basic properties of the gyre, such as its depth, freshwater content, and strength. Analytical and numerical modeling is employed to demonstrate the mechanism, contrasting equilibration processes in an ice-covered versus ice-free gyre. Our study has significant consequences for freshwater accumulation and release in a warming climate with continued sea-ice loss. We argue that reduced sea-ice extent and more mobile ice will result in the gyre becoming deeper and faster, accumulating more freshwater which will ultimately be released by Ekman upwelling mediated by the governor or instability of the gyre.

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Freshwater contribution of Greenland icebergs to the North Atlantic

The seas that surround Greenland – the Labrador Sea, in particular – are key regions where dense water is formed and exported at depth southwards, as part of the upper cell of the Meridional Overturning Circulation. The formation of dense water is, however, susceptible to the introduction of freshwater in the ocean, which increases the stability of the water column and reduces deep convection. One of the least understood sources of freshwater to the North Atlantic are icebergs, most of which are calved from Greenland Ice Sheet. By using the Nucleus for European Modelling of the Ocean (NEMO) coupled with a module that moves and melts icebergs using vertically-integrated ocean fields, we aim to evaluate the importance of dividing Greenland discharge into liquid and solid components – as opposed to introducing all discharge in liquid form – in terms of freshwater fluxes and potential impacts on Labrador Sea subduction. We also investigate if the heat flux resulting from melting the icebergs holds an important role on the North Atlantic's stratification and variability of sea ice cover.

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Sensitivity of the Arctic Sea Ice to and Its Impact on the Regional Energy Budget

We use the Regional Arctic System Model (RASM) to investigate and quantify some of the key uncertainties of the Arctic surface energy budget, including the oceanic forcing of the Arctic sea ice and the potential role of its ongoing decline in the regional and global energy imbalance. RASM is a fully coupled limited-domain ice-ocean-atmosphere-land model developed to better understand the linkages and coupling channels within the Arctic System at a process scale and to improve prediction of its change at a spectrum of timescales. Its domain is pan-Arctic, with the atmosphere and land components configured on a 50-km grid. The ocean and sea ice components are configured on rotated sphere meshes with four configuration options: 1/12-deg (~9.3km) or 1/48-deg (~2.4km) in the horizontal space and with 45 or 60 vertical layers.

The main objective of this study is to quantify the oceanic fluxes in and out from the Arctic Ocean in order to understand their sensitivity to model spatial configurations and varying parameter space as well as their impacts on the sea ice cover and regional surface energy budget. Our results imply significant variability of the total oceanic heat convergence into the central Arctic Ocean subject to different model configurations. We find that the range of uncertainty in the net oceanic heat transport is comparable to the amount of extra energy required to melt almost all the Arctic sea ice in summer. We argue that basin-wide changes in the sea ice cover contribute substantially to the regional energy imbalance, via the dramatic reduction of surface albedo and accumulation of heat in the upper ocean due to insolation.

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A Lagrangian Analysis of Arctic River Freshwater Accumulation

A dominant physical characteristic of the Arctic Ocean is the presence of a large volume, of freshwater (FW), partially due to North American and Eurasian river runoff. Rivers are a major source of FW in the Arctic Ocean with the three largest rivers (Ob, Yenesey, and Lena) in Russia and the Mackenzie, the largest in North America. FW from river sources can accumulate in the Beaufort Gyre (BG), which is estimated to hold about ten times more freshwater than the annual freshwater flux into the Arctic basin. A major factor influencing FW accumulation in the BG is the Ekman pumping process owing to the Arctic High anticyclonic wind circulation causing FW convergence and downwelling. Any change in the magnitude or direction of the wind forcing affects the FW content of the BG. In turn, the FW content can influence the extent of sea ice cover, the depth of the thermocline and halocline, as well as the energy balance of the Arctic Ocean. We investigate the role of Arctic rivers in this process by launching Lagrangian tracers at the major North American and Eurasian river basins between 1993 and 2013 using output from the Global Ocean Physics Reanalysis (GLORYS), based on the Nucleus for European Modeling of the Ocean (NEMO) model. Tracer pathways and concentrations are analyzed during cyclonic and anti-cyclonic circulation regimes. Additionally, we provide a more detailed analysis of this freshwater variability in the Beaufort Gyre region by comparing our results with observations from the moored instruments from the Beaufort Gyre Exploration Project.

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Atlantic Water pathways around Svalbard mapped using vessel-mounted current profilers

A large amount of warm Atlantic Water (AW) enters the Arctic as a boundary current through Fram Strait (West Spitsbergen Current, WSC) and is the major oceanic heat source to the Arctic Ocean. Along the North-Western Svalbard shelf, the WSC splits into the shallow Svalbard Branch, the Yermak Branch that follows the slope of Yermak Plateau, and the Yermak Pass Branch flowing across the plateau.

The WSC has previously been studied using moorings, dedicated oceanographic transects and models. In this study, we mapped the circulation patterns and AW flow around Svalbard using Vessel Mounted Acoustic Doppler Current Profiler data from multiple surveys and vessels during 4 consecutive summers (2014-2017). Despite the scattered nature of this compiled data set, persistent circulations patterns could be discerned.

Objective mapping showed a meandering boundary current west of Svalbard and a more homogeneous AW flow, centered around the 1000 m isobath north of Svalbard. In all summers, we observed a northward jet between 79 and 80 °N and the 1000 and 500 m isobaths, before the WSC divided into the three branches. North of Svalbard, the shallow Svalbard Branch reunites with the Yermak Pass Branch between 10 and 15 °E and a part of the AW circulates within Hinlopen Trench. Transport estimates in the upper 500 m compare well with the previous estimates based on different methods.

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Arctic-wide sea-ice thickness estimates from combining satellite remote sensing data and a dynamic ice-ocean model with data assimilation during the CryoSat-2 period

Exploiting the complementarities between CryoSat-2 and Soil Moisture and Ocean Salinity (SMOS) satellite sea ice thickness products, daily Arctic sea ice thickness estimates from October 2010 to December 2016 are generated by an Arctic regional ice-ocean coupled model with satellite thickness assimilated. The model is based on the Massachusetts Institute of Technology general circulation model (MITgcm) and the assimilation is performed by a local Error Subspace Transform Kalman filter (LESTKF) coded in the Parallel Data Assimilation Framework (PDAF). Our thickness estimates can be generally thought of as a model and satellite combined thickness (MSCT). Results show that the MSCT is comparable to the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) product, and meanwhile fills the gaps in melt seasons when CryoSat-2/SMOS merged sea ice thickness (CS2SMOS) is unavailable. The MSCT appears to correct some thickness biases where PIOMAS overestimates thickness in thin ice areas and underestimates thickness in thick ice areas. Comparisons with in-situ observations from the Beaufort Gyre Exploration Project (BGEP), Ice Mass Balance (IMB) Buoys and the NASA Operation IceBridge demonstrate that MSCT reproduces observed temporal and spatial variations. MSCT benefits from satellite thickness assimilation in the freezing season and from model dynamics in the melting season. Due to imperfect parameterizations in the sea ice model and satellite thickness retrievals, MSCT does not reproduce the heavily deformed and ridged sea ice along the northern coast of the Canadian Arctic Archipelago (CAA) and Greenland. The new Arctic sea ice thickness estimates can serve for assessing sea ice volume changes in recent years. We will further extend this work to a climate model focusing on the seamless sea ice prediction.

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Arctic Gateway Transport and Sensitivity in the ANHA NEMO Configuration

Here we use 1/4 and 1/12 degree versions of the Arctic and Northern Hemisphere Atlantic Configuration of the NEMO model to examine Gateway transport in and around the Arctic Ocean. We focus first on how well the model can reproduce the existing observations. We then examine the sensitivity of the model transports to Atmospheric Forcing (CORE, CGRF, ERA, etc.), runoff products (and thus freshwater distribution) as well as tidal mixing (parameterized and explicit). This examination will consider both physical transports (volume, freshwater, temperature) as well as biogeochemical (oxygen).

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An evaluation of the relationship between anomalous wind forcing, ocean heat transport and sea ice in a suite of Arctic model simulations

Morven Muilwijk[1,2], Mehmet Ilicak[3,4] , Lars Henrik Smedsrud[1,2] & the FAMOS CRF working group

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We use a suit of different Arctic Ocean model simulations from the FAMOS (Forum for Arctic Modeling and Observational Synthesis) community to analyze the effect of anomalous wind forcing in the Nordic Seas on poleward ocean heat transport, Atlantic Water transport routes and Arctic sea ice. This study is part of a coordinated modeling experiment, where the goal is to see how different models respond to abrupt ``step'' changes in external forcing fields, and to compute ``Climate Response Functions'' (CRFs). We focus on the sensitivity of Atlantic Water circulation to changes in the wind field in the Greenland Sea in relation to natural forcing variability, as manifested in the North Atlantic Oscillation (NAO).

We find that anomalous strong or weak wind forcing in the Greenland Sea, which is comparable to a strong positive or strong negative NAO index, results in changes of the Atlantic Water flow in not only the Nordic Seas and Eurasian Basin, but also all the way north into the Canadian Arctic and all the way south of the subpolar gyre. In the Barents and Kara Seas there is a linear relationship between the anomalous Atlantic Water inflows resulting from our wind perturbations and the sea ice extent and volume. The models investigated generally agree in behavior, but there is a wide spread in the strength of responses, and also some differences in the timescales and spatial patterns of the responses. This can partly be explained by the different climatological states of the models and partly by differences in Atlantic Water pathways.

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Mechanisms Controlling the Interannual Variability and Spatial Distribution of Physical Parameters in the Subarctic Northwest Atlantic

The ocean surface of the subpolar northwest Atlantic (SPNWA) is a dynamic region where the atmosphere and ocean are tightly coupled. The region is influenced by inflow of freshwater from the Arctic Ocean through the Davis Strait, Baffin Island Current and Western Greenland Current, contrasting the warm and salty contribution of Atlantic waters. The goal of this study was to determine the primary driving factors of interannual variability in sea surface temperature (SST) and surface chlorophyll-a (chl-a) by utilizing satellite (Pathfinder, SeaWiFS) and reanalysis (ECMWF and CFSR) data. Using composite analysis, variables including SST, chl-a, cloud cover, 500 mb geopotential height, surface air temperature, surface wind stress, latent heat flux, mixed layer depth, and sea ice were examined to identify the spatial fluctuations in anomalous conditions and attempt to characterize them based on the patterns of other selected parameters for the summer season July-September (JAS) following a strong NAO^{+} phase in 2000 and NAO^{-} phase in 2010. Furthermore, using season-resilient and classical empirical orthogonal function (S-EOF/EOF) analysis, spatial and temporal patterns of the variables were investigated and correlations with indices of climatic patterns, such as the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO), were found. The PCs corresponding to the first mode EOF of SST, surface air temperature, cloud cover, and GPH exhibit similar temporal variations and are all correlated at the 5% significance level with the AO with varying time lags. Significant correlations with the NAO index exist with SST, Chl, surface air temperature, sea ice, meridional wind, LHF, and GPH. The first mode of the S-EOF of SST appears to represent the recirculation of Atlantic water in the SPG, while the second is indicative of Arctic waters entering the SPNWA through the Davis Strait and Canadian Arctic Archipelago. The first mode of S-EOF applied to SST and Chl are both significantly correlated with AO and NAO indices. These correlations signify the impact of short-term climate system fluctuations on physical characteristics of the subpolar region and can be used to better represent these interactions in models.

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On the statistical properties of sea ice lead fraction and heat fluxes in the Arctic

Heat flux through leads and polynyas is an order of magnitude larger than that through unbroken ice. In this presentation we explore some statistical properties observed in Arctic sea ice lead fraction. We show that our model (neXtSIM) reproduces well the probability density function (PDF) and the monofractal spatial scaling of observed lead fluxes in the Central Arctic. Given the importance of heat flux through leads we then use the model to explore the statistical properties of the modelled heat fluxes. We show that the heat fluxes have a multifractal scaling in the Central Arctic which we attribute to lead formation, while coastal polynyas destroy the scaling in the wider Arctic. Finally we show that the scaling of simulated lead fraction is preserved for different model resolutions, while further work on a sub-grid scale parametrisation of surface heterogeneity is required to preserve the scaling of heat fluxes for different model resolutions.

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Predictability of a drastic sea ice reduction in the Arctic Ocean with climate model MIROC

The mechanisms for and predictability of a drastic reduction in the Arctic sea ice extent (SIE) are investigated using the Model for Interdisciplinary Research on Climate (MIROC) version 5.2. Here, a control (CTRL) and perfect-model ensemble prediction (PRED) experiments are conducted. In CTRL, three drastic SIE reductions occur in 200 model years regardless of forcing fixed at the year 2000. In each reduction event, the Arctic Dipole Anomaly (ADA), characterized by positive sea level pressure anomaly over the Beaufort Sea and negative over the Kara Sea, is formed in summer. The sea ice retreats in response to winds associated with the ADA, further melts due to heat input through the open water, and drastically decreases. This resembles the mechanism for the drastic ice reduction that was observed in September 2007. Analysis of the CTRL results suggest that the combined effects of the ADA and preconditioning of the Arctic Ocean interior through ocean heat transport from the North Atlantic and Pacific Oceans cause the drastic reduction in the Arctic SIE. In years experiencing drastic reductions in SIE, the September SIE can be skillfully predicted in PRED started from July, but not from April due to the inaccurate prediction of the ADA. In years with a small sea ice anomaly, the September SIE can be predicted from April due to the memory of the ocean and sea ice.

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Bio-optics of an extensive under-ice phytoplankton bloom in the Atlantic sector of the Arctic Ocean

Under-ice phytoplankton blooms are a major recent discovery and represent an emergent unknown factor in Arctic marine ecology. Their occurrence has been largely attributed to increased light transmission through a thinning and more dynamic Arctic sea-ice cover, highlighting the importance of characterisation of bio-optical properties of both sea ice and the upper ocean, and the resulting under-ice light field. Here we report on an extensive spring phytoplankton bloom dominated by the haptophyte algae Phaeocystis pouchetii, with chlorophyll a concentrations up to 7.5 mg m-3, observed under compact snow-covered Arctic sea ice at 80-81˚N north of Svalbard. The under-ice bloom changed the inherent optical properties (IOPs) of the upper ocean, resulting in elevated absorption and particularly scattering across the visible wavebands. Both absorption and scattering were dominated by phytoplankton. Measured absorption and scattering coefficients in the water were used as inputs for a 1D coupled atmosphere-ice-ocean radiative transfer model (AccuRT) to investigate effects of altered IOPs on the under-ice light field. We found substantial differences between vertical distribution of scalar and downwelling planar irradiance in open water and ice covered ocean, which needs to be taken into consideration for correct modeling of under-ice primary production. Investigated relationships between the optical, biogeochemical and biological variables provide a great potential for autonomous monitoring of the state of under-ice blooms in the wake of developing underwater technology. Our findings may also help to improve light parameterizations in under-ice primary production models and provide further basis for investigating physical-biological feedbacks using coupled physical-biogeochemical dynamic models.

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Internal Tidal Waves under the Land-fast Sea Ice in the Southeast Hudson Bay

We report the first ever collected data on internal tidal waves under land-fast in Hudson Bay complemented by remote sensing observations during ice-free season. This is significant because internal waves in the Arctic regions have been of recent scientific interest due to their role in vertical mixing, and their influence on the heat budget of the upper ocean and ice cover. As evidenced by SAR remote sensing imagery, the Belcher Islands archipelago is one of the most active regions for internal tidal wave generation in Hudson Bay due to its unique shoreline, bottom topography and proximity to an amphidromical point. Here we present and examine the first ever collected for the studied region temperature, salinity and current velocity data from the ice-tethered mooring deployed in an ice-covered narrow channel between Broomfield and O'Leary islands located in the south-east tip of Belcher islands group in Hudson Bay and discuss a possible impact of internal tidal waves on water mass characteristics.

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Stability of the land-fast bridges formed in a MEB and a VP model

Land-fast ice is an important component of the Arctic system, yet its representation in large-scale sea ice models remains a challenge, partly due to the difficult parameterization of ice fracture that governs the stability of ice bridges. This study aims at improving our understanding of how the ice bridges are maintained by the formation of ice arches at the land-fast ice edge. In particular, the process at which arching fractures are developed is investigated and their sensitivity to the yield curve parameters is discussed. We also stress that the model configuration and the coast morphology are also largely influential in determining the timing and shape of the arching fractures.

Using an ideal channel configuration, we perform a range of experiments in which the model material parameters are varied to determine their relation to the strength of the ice cover. These experiments are made using both the Elasto-Brittle and the Viscous-Plastic rheology, which are implemented using the same numerical framework. This allows us to isolate the differences in the modelled ice bridges (and ice fractures) that are due to the different choice of rheology from those that are introduced by the different model parameters, such as the time resolution and discretization.

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Atmospheric circulation modes in Arctic and their roles in interannual ice extent variability: a numerical study.

The time variability of the EOF decomposition of atmospheric forcing is considered. Tendencies associated with climatic changes of recent decades are highlighted. On the basis of numerical modeling, their contribution to the formation of Arctic ice is estimated.

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Once again: causes and mechanisms of the Beaufort Gyre freshwater changes

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A 16 year-long time series of summertime salinity of the Beaufort Gyre was compiled using data from the Beaufort Gyre Observational System established by the USA and Canada in 2003, with contributions from Japanese, Korean and Chinese expeditions to the western gyre. These data provide an unprecedented view of the summertime structure and inter-annual variability of the Beaufort Gyre atmospheric, sea ice, thermohaline stratification and geochemical characteristics. Over our 15 years of data collection, the globally-significant freshwater content of the gyre increased by 40% due to: Ekman convergence of the low salinity surface waters, from unusually-persistent, anticyclonic, wind- and ice-driven surface-stress, and extensive ice melt. The long time series now allows an empirical estimation of the end-of summer freshwater content as a function of the annual Ekman convergence and summertime melt. Inter-annual variation in the gyre can thus be viewed as a result of these two simple surface processes.

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Observations of summer sea-ice processes

Christine Provost and Nathalie Sennechael

We report continuous observations in the high Arctic over the summer season from early April (at the North Pole) to late September (still north of 84°N) at two nearby sites (A and B 10 km apart) with distinct initial conditions in terms of snow depth and ice thickness. Frequent storms brought additional snow or rain and slowed down the southward drift. Site A (initial conditions 0.5m snow, 1.4m ice) was equipped with an ice mass balance instrument (SIMBA), an ocean profiler and a web camera. Site B (initial conditions 0.1m snow, 1.90 m ice) was only equipped with a SIMBA. Site A web camera documented the evolution of a melt pond from its formation to its disappearance. The pond formed over 15 days, reached a depth of about 1.3 m above a 1.2 m of warm (> -1°C) ice, and disappeared within a few hours leading to the development of an under-ice pond that subsequently froze. A pond also developed at site B. It drained out at the same time as site A pond without any record of melt water outpouring to the ocean. The ice mass balance instruments precisely document summer processes in the snow and ice during the pre-melt, melt and refreezing periods at the two contrasted sites.

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Investigating the Spatial and Temporal Variability of the Beaufort Gyre from Satellite Observations

The Beaufort Gyre is a large reservoir of freshwater in the Arctic. In recent decades, sea surface height (SSH) and freshwater content have increased as a consequence of spin-up and extension of the gyre. A new satellite-derived dataset, based on altimetry (Armitage et al., 2016), provides the Arctic-wide SSH field in ice-covered areas over the years 2003-2014. Here we use this dataset to diagnose the seasonal to interannual variations of the characteristics of the gyre, namely the position of its center, its extension, shape and symmetry, and how they covary. We investigate the drivers of this variability by examining the interplay between bathymetric constraints, surface wind stress and sea ice variability and how they control the dynamics and temporal evolution of the gyre. We discuss the implications of these variations for the observing systems currently deployed in the regio n.

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Modelling High Frequency Variability in Hudson Strait Outflow

Freshwater outflow from Hudson Strait, mostly from river discharge from Hudson and James Bays, is the third largest source of freshwater to the North Atlantic, with observational and modelling estimates ranging between 26-31 mSv (Sref = 33). Understanding the structure of freshwater and volume fluxes to the Labrador Current has implications not only for stratification in the Labrador Sea, but also nutrient and contaminant concentrations for the fishing industry along the shores of Eastern Canada. Earlier observations have shown that anticyclonic freshwater eddies, generated by storms in Hudson Bay, carry a significant amount of freshwater in the Hudson Strait outflow. By combining both mooring observations and a high spatial (4.5 km) and temporal (6 hours) coupled sea ice-ocean model simulation, we investigate the presence of these freshwater eddies and variability in the freshwater outflow. We find that the model is able to simulate the anticyclonic freshwater eddies, however, they do not account for the large fluctuations seen in the volume and freshwater flux transports. Variability in the position and size of the freshwater jet is explored, in addition to generating processes.

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The contribution of the tide to mixing at intermediate depths in the Arctic Ocean

Tom P. Rippeth[1], Vasiliy Vlasenko [2], Nataliya Stashchuk [2], Brian D. Scannell [1], J. A. Mattias Green [1], Ben J. Lincoln [1], and Sheldon Bacon [3]

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The tides are a major source of the kinetic energy supporting turbulent mixing in the global oceans. The prime mechanism for the transfer of tidal energy to turbulent mixing results from the interaction between topography and stratified tidal flow leading to the formation of freely propagating internal waves at the period of the forcing tide. However, poleward of the critical latitude (where the period of the principal tidal constituent exceeds the local inertial period), the action of the Coriolis force precludes the development of freely propagating linear internal tides. Here we focus on a region of sloping topography, poleward of the critical latitude, where there is significant conversion of tidal energy. A high-resolution non-linear modelling study demonstrates the key role of super-critical flow (Froude number, $Fr > 1$), associated with tidally generated lee waves, in the transfer of energy from the barotropic tide to internal waves in these high latitude regions. Time series of flow and water column structure made in the region of interest show internal waves of characteristics which are consistent with those predicted by the model, and concurrent microstructure dissipation measurements show significant levels of mixing associated with these internal waves. The results imply that tidally generated lee-waves are a key mechanism for the transfer of energy from the tide to turbulence poleward of the critical latitude but that the tidal energy pathways to TKE dissipation and mixing may differ from that equatorward of the critical latitude.

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Factors controlling seasonal mixed-layer freshening in the Canada Basin during 1975, 2006, and 2007

The Canada Basin has experienced rapid sea ice retreat, with trends toward warmer, shallower, and fresher mixed layers. These changes to the upper ocean have impacted upper-ocean heat storage processes that influence sea ice evolution. In particular, observations indicate that the seasonal halocline has strengthened, allowing more heat to be stored in the near-surface temperature maximum layer for a longer period of time. Several previous studies have suggested that the strengthening of the seasonal halocline is a result of enhanced summer sea ice melt, which causes more seasonal mixed-layer freshening. Here, we examine observed seasonal mixed-layer freshening in 1975, 2006, and 2007 using an idealized, one-dimensional mixed-layer salinity budget. Consistent with previous studies, our results indicate that in 2006 and 2007 mixed layers underwent 2-3 times more seasonal freshening than in 1975. Using our idealized framework, we examine factors causing this difference by estimating changes to (1) the heat flux to the sea ice, (2) freshwater flux from sea ice melt, and (3) the resulting seasonal mixed-layer salinity evolution. The results indicate that compared to 1975, the heat flux to the sea ice has increased by ~20-60% in 2006-2007. However, we estimate that the freshwater flux from sea ice melt has only increased by ~5-20%. These results imply that while the ocean-driven heat flux has increased in recent years, there is also less sea ice available to melt. Our estimate, therefore, suggests that the increased mixed-layer freshening in 2006-2007 relative to 1975 can be attributed mainly to shallower mixed layers, which cause similar amounts of freshwater to be concentrated within a smaller volume.

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Impact of small-scale coupled atmosphere-ice-ocean interactions: Results from the Canadian high-resolution forecasting system for YOPP

In the context of the Year of Polar Prediction (YOPP, 2017-19), a pan-Arctic coupled atmosphere-ice-ocean model has been developed to investigate the impact of coupled interactions in daily 48h forecasts produced in real-time during YOPP. The atmospheric component, the Canadian Arctic Prediction System (CAPS), runs over a regional 3 km grid spacing domain and has the latest innovations from the Global Environmental Multiscale (GEM) model, including a new Prediction Particle Properties (P3) microphysics scheme (clouds, precipitation). During the forecast, the atmospheric model is coupled at each time step to an ice-ocean model running over a regional 3-8 km grid spacing domain, covering the Arctic and North Atlantic regions, namely the Regional Ice-Ocean Prediction System (RIOPS). RIOPS uses the NEMO-CICE ice-ocean model and includes explicit tides, a landfast ice parametrization based on the effect of grounded ice ridges (for improved representation over shallow waters), and an increased resistance to tension and shear in the ice rheology (for improved representation in land-locked areas). Each time step CAPS sends its surface state variables to RIOPS that computes in exchange detailed surface fluxes (momentum, heat and moisture) over the open ocean and the ice pack, aggregating them over the multi-thickness ice distribution. Results are presented from coupled and uncoupled forecasts showing the impact of coupled interactions at regional and basin scales. In particular the effect of lead fractions and wind channeling in the Canadian Arctic Archipelago are discussed. Additionally, it is shown that details of sea ice model physics can affect small-scale sea ice features (coastal polynyas, ridging) which in turn result in a tangible impact on atmosphere-ice-ocean fluxes of heat and moisture.

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Connections between thermohaline staircases and double-diffusive intrusions

Bert Rudels, Meri Korhonen, Vladimir Ivanov, Benjamin Rabe, Ursula Schauer

The Nansen Basin is where the Atlantic water entering the Arctic Ocean experiences its largest transformations. The upper part of the Fram Strait inflow branch becomes cooled and diluted by heat loss and sea ice melting, eventually forming the Polar surface water and creating the underlying halocline and thermocline susceptible of double diffusive fluxes from the warm Atlantic core to the surface layer. In the eastern part of the Nansen Basin the inflow of cooled and freshened Atlantic water entering over the Barents Sea creates strong lateral fronts in temperature and salinity that eventually evolve into thermohaline intrusions spreading into the cores of the two water masses. There are thus two processes that may create thermohaline staircases; either vertically by cooling of the thermocline and halocline from above or laterally by overturning thermohaline intrusions. The thickness of the homogenous layers depends in the first case on the density anomalies created at the diffusive interfaces and the initial background stratification. In the second case staircases will form, if a strong front is present in the diffusively unstable layer above the temperature maximum. The temperature steps then become larger at the diffusive interfaces than the salinity steps at the saltfinger interfaces and the stronger buoyancy flux through the diffusive interfaces leads to overturning of the saltfinger interface and the formation of staircases. The homogenous layers created in this way are much thicker than those formed by cooling a density gradient from above. In recent years staircases with 50m to 100m thick layers have been observed in the Nansen Basin, while the intrusions previously present in the stable-stable part between the temperature maximum and the salinity maximum have become less frequent. One possible explanation for this change could be that part of the Barents Sea inflow branch has become less dense, either warmer or less saline, and interacts with the Fram Strait branch higher up in the water column, creating intrusions that eventually transform into thermohaline staircases.

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Fully coupled sea ice – ocean – wave modelling for sea ice retreat

Projections indicate that in the future marginal ice zones, where waves play an important role, will be found in large parts of the Arctic Ocean. We are developing a fully coupled sea ice – ocean and waves model to be able to model these areas more accurately, allowing for the most comprehensive set of ocean and ice interactions and feedbacks. We focus on some important feedbacks that can accelerate ice decline. The first one is the lateral melting feedback, which depends on the floe break-up due to waves. Waves also change currents due to Stokes drift and increase mixing. Only a fully coupled simulation makes it possible to model both swell and waves generated in the presence of sea ice realistically. We present initial results from a coupled NEMO-CICE-wave simulation. We analyse wave attenuation, wave break-up and examine the effect of waves on the ice dynamics and thermodynamics. We also examine storm events in the Arctic and their link to extreme ice retreat episodes in summer.

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Coordinated Arctic Acoustic Thermometry Experiment (CAATEX)

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The Arctic region is experiencing strong climate change, yet the deep Arctic Ocean under the sea ice is sparsely observed and remains largely unknown. The recently funded CAATEX project is designed to address three major research questions:

•What is the spatiotemporal variability of mean ocean temperature in the central Arctic Ocean?
•How do local atmosphere-ice-ocean interaction processes vary between seasons and regions?
•How well do climate models estimate the heat content of the Arctic Ocean?

Our approach is to use basin-wide acoustic thermometry and ocean point measurements in combination with an eddy-resolving ice-ocean model.

In 2018 and 2019 our effort will be to design and implement the acoustic thermometry experiment including six fixed moorings across the Arctic Basin from North of Svalbard and to the Beaufort Sea. . The mooring system will be deployed in September 2019 and recovered in 2020. In the Beaufort Sea the moorings will be deployed using the USCGC Healy, whereas the moorings north of Svalbard will be deployed by KV Svalbard.

The moored acoustic network will provide year-round measurements of acoustic travel times between each of the moorings. The measured travel times will be inverted for range-averaged ocean sound speed which is a proxy for range- averaged ocean temperature. In this way the mean ocean temperature will be measured for a large part of the Arctic Ocean.

A variety of acoustic paths along with time series of oceanographic point measurements at each fixed mooring at different depths from close to surface down to the deep ocean will provide depth resolution of the heat content. The CAATEX measurements will be along a line to similar observations conducted during the TAP (1994) and ACOUS (1999) allowing for historical comparison.

Travel time measurements will also be made between the source moorings and several drifting receiver buoys provided by a Canadian program. One of the CAATEX drifting receivers will be coordinated with the MOSAiC campaign which will allow easy deployment and recovery as it drifts with the Polarstern.

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Integrated Arctic Observing System (INTAROS) and the way towards a sustained integrated Arctic Observing System.

Stein Sandven and Hanne Sagen
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The INTAROS consortium

The main objective of H2020 project INTAROS is to develop an integrated Arctic Observation System by extending, improving and unifying existing systems in different Arctic regions. The final deliverable from the project is a roadmap for implementation of a sustained integrated Arctic Observation system. This requires extensive coordination, mobilization and cooperation between the existing international and national observing platforms, technology developers, modelling communities and other relevant stakeholders. Any sustainable ocean observing systems in the Arctic depend on long-term funding, and that funding mechanisms other than research programs should be used for this. To achieve this, we need to engage user groups within and outside the scientific community. How can this be done? The development of sustained observations can only be done in close collaboration with stakeholders groups who have responsibilities for climate and environmental monitoring, marine safety, water quality, resource management and forecasting services in the Arctic.

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Biogeochemical operational modeling in the Arctic using the TOPAZ forecasting system

The TOPAZ system includes model components for ocean, sea-ice, biogeochemistry and data assimilation. The system is used for basic research, but its main application is in operation oceanography as the central tool used to provide marine forecasts in the CMEMS Arctic Marine Forecasting System. The focus is on the North Atlantic and Arctic, though the present model covers the entire North Atlantic. The physical system has been operational for more than 10 years, while the biogeochemical model started operationally since 2011. In addition to 10-day forecast, we are also producing long-term reanalysis, for the biogeochemistry this includes the assimilation of biogeochemical variables. This was recently expanded from only assimilating ocean colour to also assimilating in-situ measurements of nutrient in the water column.

The present biogeochemical model consists of the biogeochemical model ECOSMO coupled to the ocean model HYCOM. Recent development of this model includes the addition of prognostic chlorophyll and addition of carbon chemistry. In addition a module for calcifying algae has been added as an option in the model.

This presentation will give an overview of the operational system, its present capabilities and the next developments of the system.

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The Formation of Double-Diffusive Layers in the Weakly-Turbulent Arctic Ocean

Double-diffusive stratification in the ocean is characterized by staircase structures consisting of mixed layers separated by high-gradient interfaces in temperature and salinity. These double-diffusive layers, which can transfer heat vertically towards sea ice, have been found over a vast region of the Arctic Basin. Several past studies have examined the formation of these layers. In one formalism, the mixed-layer thickness is set by layer formation that arises when a heat source is applied at the base of water that is stably-stratified in salinity. We extend this work to consider the effect of intermittent turbulence on double-diffusive layer formation. We find that there is a critical diffusivity ratio (ratio of salinity diffusivity to thermal diffusivity) above which a staircase cannot form. We also find that layers decrease in thickness with height in the staircase, a function of the decreasing heat flux into a layer with height. This variation in layer thickness with height is also observed in Arctic measurements of the double-diffusive staircase. Finally, results suggest that increased diffusivity ratios lead to decreased heat fluxes across interfaces. The study has implications for the weakly turbulent Arctic Ocean where double-diffusive staircases are widely present and mixed-layer thicknesses are well-resolved by ocean measurements.

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Freshwater response of the Beaufort Gyre to a step change in the Beaufort High: model comparisons

We study the response of the freshwater content of the Beaufort Gyre to a step change in the Beaufort High across a range of Arctic Ocean models.

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Using CryoSat-2 sea ice thickness to improve sea ice evolution in the ocean – sea ice model NEMO-CICE

David Schroeder, Danny Feltham, Michel Tsamados & Rachel Tilling

Estimates of Arctic sea ice thickness are available from the CryoSat-2 radar altimetry mission during the ice growth seasons since 2010. We find that a default simulation with the sea ice model CICE strongly underestimates ice thickness in the central Arctic, despite reproducing the inter-annual variability of summer sea ice extent. We can identify the underestimation of winter ice growth being responsible and show that increasing the ice conductive flux for lower temperatures (bubbly brine scheme) and accounting for the loss of drifting snow results in the simulated sea ice growth being more realistic. Our optimal model configuration does not only improve the simulated sea ice thickness, but also summer sea ice concentration, melt pond fraction, and length of the melt season. Sensitivity studies reveal that in the central Arctic atmospheric winter conditions have little impact on winter ice growth due to a dominating negative feedback process: the thinner the ice and snow in autumn, the stronger the ice growth in winter. Applying the improved CICE setup in coupled simulations with the ocean model NEMO improves the sea ice evolution in the central Arctic in the same way as for the stand-alone CICE simulations highlighting the importance of the sea ice physics. In addition, the coupled configuration allows us to examine the strength of feedback processes in the marginal ice zone.

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Atlantic Water heat transport variability in the 20th century Arctic Ocean

Authors: M. Muilwijk, Lars H. Smedsrud, M. Ilicak, and Helge Drange

Presentor: Lars H. Smedsrud

Northward ocean heat transport and its variability influence the Arctic sea ice cover, contributes to surface warming or cooling, or simply warms or cools the Arctic Ocean interior. A simulation with the forced global ocean model NorESM20CR, aided by hydrographic observations since 1900, show large decadal fluctuations in the ocean heat transport, with largest variations in the Atlantic sector. The simulated net poleward ocean heat transport over the last century is about 68 TW, and 88% of this occurs in the Barents Sea Opening (45 TW) and the Fram Strait (15 TW). Typical variations are 40 TW over time scales between 5–10 years, related to thermohaline and wind stress forcings. The mean heat transport in the Davis Strait is about 10 TW, and less than 5 TW flows north in the Bering Strait. The core temperature of the Atlantic Water (AW) entering the Arctic Ocean has increased in recent decades, consistent with an ongoing expansion of the Atlantic domain (Atlantification), but earlier warm events are also documented. The temperature of the northward flowing AW thus plays a vital role, with decadal variations of around 0.5 C.

The Nordic Seas atmosphere contributes with thermodynamic forcing, dampening the advected heat anomalies. In the Barents Sea, variations in the inflow volume flux dominate, while variations in temperature dominate the heat transport in the Fram Strait. There are significant trends over recent decades, also dominated by the Barents Sea that presently has 1 Sv higher volume transport and +1:0 C warmer AW than the long-term mean.

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Event-driven release of upper ocean heat in the autumn Canadian Arctic Ocean

Solar heat stored in the upper ocean can play a significant role in delaying autumn advance of sea ice cover in the Canadian Arctic Ocean. In particular, episodic entrainment of heat from the near-surface temperature maximum (NSTM) during high wind events can briefly reverse ice advance by melting newly formed ice. Such an event was observed in October 2015, during the ONR Arctic Sea State campaign. Here, we will present the evolution and outcome of this event as a motivation for including coupled mixed layer models in regional Arctic modeling. High resolution observations of the air-ice-ocean system during the October 2015 event showed that approximately 3-5 cm of new pancake sea ice was melted over the course of three days as a result of heat entrained from the upper ocean. The total amount of heat lost was substantial compared to prior studies under multi-year ice, but with a larger portion accounted for by atmospheric heat fluxes. The magnitude of heat lost and ice melted was likely related to the increasing wave climate in the autumn Arctic Ocean, where waves during this event reached nearly 5 m. Whether wave energy plays a significant role in mixing the upper ocean is indicated to be a function of the fetch that is available. These results suggest that the enhancement of mixing due to surface waves should additionally be considered in Arctic mixed layer modeling. Observations during this event will also be used to explore the kinematics and dynamics of pancake ice floes during sea ice formation

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Inversion of acoustic travel times from the UNDER-ICE tomographic experiment

The Fram Strait is the only deep-water connection between the Arctic ocean and the Atlantic Ocean, and consequently the main gateway for the heat-exchange between these oceans. An acoustic system for acoustic thermometry was developed under the ACOBAR project. Results from this experiment showed that it was important to monitor the heat content in the north-going West-Spitzbergen current and the south-going East-Greenland current separately. It was also found that it was difficult to separate the different arrivals of the acoustic signals in the time domain due to the complex oceanographic conditions in this region.

In 2014, five moorings were deployed in the Fram Strait for a two-year long acoustic tomography experiment under the UNDER-ICE project, funded by the Research Council of Norway. Two transceiver moorings and three receiver moorings were arranged in a pattern designed to sample both the north-going West-Spitzbergen current and the south-going East-Greenland current, with a total of eight source-receiver paths. Transmissions were made every third hour for the duration of the experiment.

Acoustic travel times were inverted to obtain the range-depth average sound-speed along the source-receiver transects. The inversion technique has previously been applied to data from the DAMOCLES and ACOBAR projects, where modelling of the small mesoscale variability is introduced to better match the observations. In the present work, this technique is applied to the data from the UNDER-ICE experiment, and development to further exploit the observations.

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Modulation of Sea Ice Melt Onset and Retreat in the Laptev Sea by the Timing of Snow Retreat in the West Siberian Plain

Recent years have seen growing interest in improving seasonal predictions of Arctic sea ice conditions, including the timing of ice retreat and ice advance, especially on the regional scale. Through its influence on albedo, the timing of seasonal melt onset is a potentially important source of predictability. This paper investigates potential links between regional sea ice melt onset and retreat in the southern Laptev Sea and retreat of terrestrial snow cover. Past studies have shown that variability to snow extent over Eurasia can substantially impact regional atmospheric circulation patterns over the North Pacific and Arctic Oceans. It is shown here that for the Laptev Sea, earlier melt onset and retreat of sea ice are encouraged by earlier retreat of snow cover over the West Siberian Plain. The circulation response to earlier snow retreat in spring is greater ridging (e.g., at 500 hPa) over the East Siberian Sea through the summer. This results in more frequently southerly flow of warm, moist air over the Laptev Sea. The relationship could provide modest improvements to predictive skill for sea ice melt onset and retreat in the southern Laptev Sea at lead times of approximately 50 and 90 days, respectively. The de-trended time series of snow retreat in the West Siberian Plain explains 26% (29%) of the de-trended variance in southern Laptev Sea melt onset (retreat).

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The new CliC/CLIVAR Northern Oceans Regional Panel; scientific motivation, objectives and plans

The Arctic Ocean is rapidly transitioning into a new regime with lower sea ice extent and increasingly younger and thinner sea ice pack. The emergent properties of the future Arctic Ocean are yet to be determined since altered feedback processes between ice, ocean, and atmosphere impact upper ocean heat content, atmospheric circulation, atmospheric and oceanic stratification, the interactions between subsurface/intermediate warm waters and surface cold and fresh layer, cloud cover and ice growth, among other properties. A new international panel, the CliC/CLIVAR Northern Oceans Regional Panel, has been established to coordinate efforts that will enhance our ability to monitor the coupled system, understand the driving mechanisms of the system change from a coupled process perspective, and predict the evolution of the emerging "New Arctic" climate in the context of the global climate system. This talk will discuss the scientific motivation for the new panel, its near-term objectives, and plans for deliverables. Topics include the two-way feedback between the Arctic and lower-latitudes, changes to the Arctic Ocean circulation, the local coupling between ocean, sea ice and atmosphere, the role of the Greenland ice sheet, future Arctic amplification, and assessments and improvements of model reanalyses, forecasts and projections.

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Overview of Arctic Sea State and Boundary Layer Physics Program

A large collaborative program has studied the coupled air-ice-ocean-wave processes occurring in the western Arctic during the autumn ice advance. A curated dataset from the associated field campaign in 2015 is now available for model testing and synthesis. Here, we summarize the results recently presented in a special issue (J. Geophysical Research) and encourage further modeling studies with the dataset. The overall view is of an Arctic shifting to a more seasonal system. The dramatic increase in open water extent and duration in the autumn means that large surface waves and significant surface heat fluxes are now common. When refreezing finally does occur, it is a highly variable process in space and time. Wind and wave events drive episodic advances and retreats of the ice edge, with associated variations in sea ice formation types (e.g., pancakes, nilas). This variability becomes imprinted on the winter ice cover, which in turn may affect the melt season the following year.

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Impact of Retreating Tidewater Glaciers on Fjord Circulation: Comparing Present Day and Future Scenario Fjord Circulation in Kongsfjorden, Svalbard

Tidewater glaciers in Kongsfjorden, Svalbard, are retreating, and it is expected that these will terminate on land at some time in the future. The transition from a tidewater glacier fjord to a fjord with only land terminating glaciers is likely to cause changes in the fjord circulation, with further implications for the biogeochemistry and ecosystem in Kongsfjorden. We compare the present day circulation and predicted future circulation in the fjord by use of the ocean model system ROMS, with the aim to quantify changes in physical parameters that impact the fjord circulation. The model setup for the present day Kongsfjorden area is based on a ROMS model with 160m horizontal resolution and 35 vertical S-coordinates. Atmospheric forcing is provided by 3km WRF data, climatology at lateral open boundaries is provided by a larger domain 800m resolution ROMS model, and fresh water discharges are provided by SnowModel output, where discharge from 3 tidewater glaciers are treated as subglacial sources. A coastline for the future scenario has been constructed based on ice-penetrating radar data. Setup for the future scenario is identical to the present day case, except for the new coastline configuration and associated location of fresh water discharge sources.

Our study found that the removal of subglacial discharges in the inner part of the fjord would substantially reduce volume fluxes in the inner part of the fjord, and result in an increased stratification during the summer months. The increase in fjord extent landward due to removal of tidewater glaciers resulted in a slight increase in tidal velocities, in particular for overtide components, but this effect was not strong enough to compensate for the removal of fresh water plumes at tidal glacier fronts. Fresh water content (salinity < 34.8) in the fjord during the melting season is predicted to increase in the future, primarily due to enhanced retention of fresh water in the inner parts of the fjord. However, fresh water in the future will mostly be confined to a thin surface layer whereas at present fresh water is found in a thicker layer, in particularly near tidewater glacier fronts.

Changes in the fjord circulation are likely to have an adverse effect some of the existing fauna in Kongsfjorden, in particular species that have their main feeding areas at tidewater glacier fronts, but these changes may also make the fjord more attractive as a refuge for arctic benthos

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Assessment of ten ocean reanalyses in the Arctic

Global and regional ocean reanalysis products (ORAs) are increasingly used in polar research, but their quality remains to be systematically assessed. To address this, the Polar ORA Intercomparison Project (Polar ORA-IP) has been established following on from the ORA-IP project. Several aspects of ten selected ORAs in the Arctic were addressed by concentrating on comparing their mean states in terms of snow, sea ice, ocean transports and hydrography. Most polar diagnostics were carried out for the first time for a such an extensive set of ORAs. For the multi-ORA mean state, we found that deviations from observations were typically smaller than individual ORA anomalies, often attributed to offsetting biases of individual ORAs. The ORA ensemble mean therefore appears to be a useful product and, while knowing its main deficiencies and recognising its restrictions, it can be used to gain useful information on the physical state of the polar marine environment.

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Impact of assimilating a merged sea ice thickness from Cryosat-2 and SMOS in the Arctic reanalysis

Accurate forecast of Sea Ice Thickness (SIT) represents a major challenge for Arctic forecasting systems. The new CS2SMOS SIT product merges measurements from the CryoSat2 and SMOS satellites and is available weekly during the winter months since October 2010. The impact of assimilating CS2SMOS is tested for the TOPAZ4 system - the Arctic component of the Copernicus Marine Environment Monitoring Service (CMEMS). TOPAZ4 currently assimilates a large set of ocean and sea ice observations with the Deterministic Ensemble Kalman Filter (DEnKF). Two parallel reanalyses are conducted with and without assimilation of the previously weekly CS2SMOS for the period from 19th March 2014 to 31st March 2015. The SIT bias (too thin) is reduced from 16 cm to 5 cm and the RMSD decreases from 53 cm to 38 cm (reduction by 28%) when compared to the simultaneous SIT from CS2SMOS. Furthermore, compared to independent SIT observations, the errors are reduced by 24% against the Ice Mass Balance (IMB) buoy 2013F and by 11% against SIT data from the IceBridge campaigns. When compared to sea ice drift derived from International Arctic Buoy Program (IABP) drifting buoys, we find that the assimilation of C2SMOS is beneficial in the sea ice pack areas, where the influence of SIT on the sea ice drift is strongest, with an error reduction of 0.2-0.3 km/day. Finally, we quantify the influence of C2SMOS compared to the other assimilated data by the number of Degrees of Freedom for Signal (DFS) and find that CS2SMOS is the main source of observations in the central Arctic and in the Kara Sea. These results suggest that C2SMOS observations can be safely included in Arctic reanalyses.

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Impacts of Recent Sea Ice Decline on Arctic Ocean freshwater storage

The freshwater stored in the Arctic Ocean is an important component of the global climate system. Currently the Arctic liquid freshwater content (FWC) has reached a record high since the beginning of the last century. The cause of the freshwater accumulation is not well understood yet. In this study we use numerical simulations to investigate the impact of sea ice decline on the Arctic liquid FWC and its spatial distribution. The global unstructured-mesh ocean general circulation model FESOM with 4.5 km horizontal resolution in the Arctic region is applied. The simulations show that the sea ice decline increases the FWC by freshening the ocean through sea ice meltwater, and modifies the upper ocean circulation at the same time. These two effects work together, which significantly increases the freshwater stored in the Amerasian Basin and reduces its amount in the Eurasian Basin. The salinification of the upper Eurasian Basin is mainly caused by the reduction in the proportion of Pacific Water and the increase in that of Atlantic Water. Consequently, the sea ice decline did not directly contribute to the observed rapid increase in the Arctic total liquid FWC. However, the changes in the freshwater spatial distribution in the Arctic Ocean indicate that the influence of sea ice decline on the ocean environment is remarkable. This study suggests that all the dynamical processes that can be altered by sea ice decline should be taken into account in order to better understand and predict the Arctic Ocean changes.

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Multi-model intercomparison of ice algal productivity on the Arctic sub-region scales

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Biogeochemical responses to the Arctic sea ice decline have become an important topic for a variety of communities. Ice algae are an important component of the Arctic marine ecosystem and carbon cycle. Generally, sea ice decline plays both positive and negative roles in ice algal biomass. For example, sea ice thinning enhances light penetration into the skeletal layer at the ice-ocean interface. On the other hand, reduction in net thermal ice growth restricts nutrient availability. Retreat of sea ice margin causes shrinking of ice algal habitat. Numerical modeling is a powerful tool to evaluate the impacts of sea ice decline on ice algal productivity on the pan-Arctic and decadal scales. In recent years, the modeling target region has been extended from landfast ice stations to the entire Arctic Ocean, and complex ice algal processes are now numerically formulated in various ways.

The present study addresses seasonal and decadal variations in ice algal productivity from 1980 to 2009, which were simulated by five pan-Arctic and global sea ice-ocean ecosystem models participating in the Forum for Arctic Modeling and Observational Synthesis (FAMOS) project. Relationships among ice algal productivity/biomass, sea ice concentration, snow depth, sea ice thickness, and nutrient contents in the sea ice column and the ocean surface layer averaged over four sub-regions (Chukchi Sea, Canada Basin, Eurasian Basin, and Barents Sea) are particularly focused on. The FAMOS models simulated reasonable seasonal cycles of the analyzed sea ice and ocean properties, whereas their amplitudes are partly different. The simulated ice algal biomass shows no common decadal trend probably because sea ice decline has both positive and negative impacts. More details with uncertainties will be reported.

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Seasonal and Spatial Variability in the Fully-Coupled Ocean-Atmosphere Surface Energy Budget: Climatology and Projections

Arctic sea ice concentration and thickness have declined due to greenhouse gas radiative forcing and a net positive climate feedback. The link between sea ice and atmosphere-ocean exchanges of energy has, however, not been heavily studied. This study evaluates the Arctic surface energy budget using a 33-member ensemble of the fully-coupled Community Earth System Model 1. The ensemble-mean and ensemble variability of trends are calculated from 2011-2040, the time period of most severe and consistent sea ice loss. The spatial and seasonal distribution of both climatology and trends in the Arctic surface energy budget vary substantially for the radiative and turbulent fluxes (shortwave, longwave, sensible heat, and latent heat), though much of this heterogeneity can be linked to spatial and seasonal changes in sea ice. Four regions stand out for their disparate projections: the Central Arctic, the Chukchi Sea, the Barents Sea, and the Greenland-Iceland-Norwegian Seas. Areas with year-round ice coverage in 2040 like the Central Arctic have a simple energy budget in which shortwave absorption is offset by a steady amount of longwave release throughout the year which does not change much over the course of the 30-year interval. The Chukchi and Barents Seas transition from persistent to marginal ice coverage, resulting in increased summer shortwave absorption that is generally overcompensated by enhanced turbulent heat flux in the late fall and early winter. Marginal sea ice in the northern Greenland-Iceland-Norwegian Seas is effectively removed in the projections, resulting in highly variable but generally strong decreases in the upward turbulent and longwave fluxes as sea ice is lost even in winter; a large ensemble variability results from the attendant ensemble spread in sea ice loss projections. Averaged over the whole Arctic, the change in the energy budget is qualitatively similar to that of the Central Arctic: loss of Arctic sea ice results in increased shortwave absorption during the summer which is mostly offset through enhanced longwave release, but how these fluxes are altered is highly geographically and seasonally dependent. Drawing physically conclusive links between sea ice concentration declines and impacts on oceanic/atmospheric circulations requires further understanding of the Arctic energy budget, particularly which components are modified and where/when these changes take place with respect to reduced sea ice.

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Progress on the neXtSIM-F forecast platform

This talk summarises progress and directions on the neXtSIM-F forecast, based on the neXtSIM (neXt-generation Sea Ice Model) sea ice model. The platform is a stand-alone sea ice model forced by ECMWF atmospheric fields and TOPAZ oceanic fields. Observational data is used daily to correct the initial fields for each forecast run, and this talk will concentrate on the benefits of some different methods of doing this.

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The 2016–2017 deep-water Canada Basin Acoustic Propagation Experiment (CANAPE): An overview

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The Arctic Ocean is undergoing dramatic changes in the ice cover and ocean structure, affecting both acoustic propagation and ambient noise. For the 2016–2017 deep-water Canada Basin Acoustic Propagation Experiment (CANAPE), five acoustic transceivers were deployed in a pentagon with a sixth transceiver at the center, forming an ocean acoustic tomography array with a radius of 150 km. The goals were to (1) understand the impacts of changing sea ice and oceanographic conditions on acoustic propagation and fluctuations, (2) characterize the depth dependence and temporal variability of the ambient noise field, and (3) determine whether acoustic methods, together with other measurements and ocean-sea ice modeling, can yield estimates of the time-evolving ocean state useful for understanding the local ocean dynamics and for making improved acoustic predictions. Each transceiver had a 250-Hz broadband source at 175-m depth in the Beaufort Duct and a vertical receiving array spanning 135 m located above the source. A Distributed Vertical Line Array (DVLA) receiver spanning 540 m was embedded within the tomographic array to provide measurements of acoustic time fronts and their fluctuations. The tomographic array was largely in open water during summer, in the marginal ice zone as it transitioned across the array during the spring and autumn, and under complete ice cover during winter. The tomographic travel-time data will initially be used in conventional stochastic inversions to obtain the large-scale temperature and current fields. In the longer term, the tomographic data, together with other data, will be combined with a regional implementation of an ocean-sea ice model embedded in a larger-scale model (e.g., Arctic Subpolar gyre sTate Estimate (ASTE)) to make dynamically-consistent ocean state estimates throughout the year.

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Pathways and watermass transformation of the Atlantic Water entering the Nordic Seas through Denmark Strait in two high resolution ocean models

The pathways and water mass transformation of the North Icelandic Irminger Current (NIIC) in the Nordic Seas are investigated by tracing the NIIC watermass in two ocean circulation models: the Modular Ocean Model (MOM) and the Parallel Ocean Program (POP). The two simulations use identical atmospheric forcing and have a horizontal resolution of 0.1 degree. However, the models differ strongly in their representation of the sea-ice cover in the Nordic Seas and, possibly as a consequence, display a different hydrography. This study is motivated by the strong connection between the NIIC and the Denmark Strait Overflow Water (DSOW) suggested from observations. However, our Lagrangian analysis shows that only 0.2 Sv of the entering NIIC exits as DSOW in the two models. In POP, the main transformation to dense water takes place along a short path north of Iceland. In MOM however, the contributing part of the NIIC to DSOW takes a large path through the Nordic Seas and reaches Denmark Strait as part of the East Greenland Current (EGC). A small contribution of the NIIC water mass to the Iceland Scotland Overflow Water (ISOW) is found in both MOM and POP (7.8%, respectively 2.1% of the NIIC). In the models studied, the water mass of the NIIC that is not connected to the overflows takes many different pathways through the Nordic seas. In any case, the pathway of the water is largely determined by the nature of the water mass transformation that the water mass experiences north of Iceland. Analysis of the thermohaline properties of the NIIC along the different pathways shows that further water mass transformations occur along the outer rim of the Nordic Seas, rather than in the interior of the basin.

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Modelling regional variability of carbon export efficiency in the North Atlantic and the Arctic

We investigate generic algorithms to improve variability in modelled carbon export by emphasizing the influence of plankton community structure. We conducted tests on a 1D lower trophic level model set at various time-series stations in the North Atlantic, and each community was allowed to modify the settling and re-mineralization rates of detritus based on their traits (i. e. diatoms produce fast sinking particles with higher re-mineralization rates, while particles from prokaryotes are slower with lower re-mineralization rates). Additional tests were conducted on aggregation, mineral ballasting and DVM. Results indicate that a community-based scheme is superior in representing temporal and spatial changes in export and transfer efficiencies without any region specific parameterization. As communities adapt to different hydrography, so does the regional export efficiency. Regional comparisons show that high latitudes, which sustain larger plankton, receive higher export efficiencies compared to both low latitudes and experiments using constant global rates. Such an export mechanism has important implications in regional and global models, since hydrography is thus tightly coupled to export through community structure, which may improve predictive skills for future ocean communities and carbon export. We present experiments in 1D from subtropics to Arctic, as well as initial tests in the Arctic in a 3D model.

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Arctic Sea Ice Geoengineering Simulated with the AWI Climate Model

The decrease of Arctic sea ice extent and volume exhibits an alarming negative trend to the point that multiple studies indicate a largely ice-free Arctic in late summer by the mid 21st century. To counteract global warming and the amplified Arctic warming in particular, proposed geoengineering strategies include the management of Arctic sea ice. An example is the employment of wind-driven pumps to spread seawater on existing sea ice in the winter months. This would allow to bypass the insulating effect of sea ice; since the water would be in direct contact with the cold atmosphere and freeze, the sea ice thickness would consequently increase, allowing more sea ice to survive the summer melt.
We test this geoengineering strategy with a climate model where it is relatively simple to modify the physical parameterizations in a way that the effect of such wind-driven pumps is mimicked. Specifically, we modify the heat and moisture flux parameterizations such that atmosphere-ocean fluxes over sea ice are computed as if the atmosphere was in direct contact with ocean water at the freezing point. We simulate several century-long CMIP-type scenarios with the AWI Climate Model to study the response of the climate system, in the Arctic and globally, varying the strength of the perturbation. We also analyze what happens in response to an abrupt suspension of the pumps to explore the reversibility of the manipulation.

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Evaluation of the high-resolution FESOM simulation in Pacific Sector of the Arctic

In the last four decades, observations show a significant decline in Arctic sea ice. Loss of the ice cover increases solar radiation and wind exposure, resulting in changes on ice drift velocities, oceanic heat and freshwater budget. The Pacific sector of the Arctic is one of the most violent areas of sea ice retreat. In this work, we evaluated the high-resolution (up to 4.5 km) Finite-Element Sea-Ice Ocean Model (FESOM) simulation results in the Pacific sector. FESOM is a new approach to simulate the global ocean circulation with variable mesh resolution and allows to resolve key regions, coastlines or narrow straits without involving additional nesting techniques. The model-simulation was in good agreement with available observed sea ice and ocean properties, especially on representation of the Pacific Water Inflow and the Beaufort Gyre. This is a good base for what we intended to investigate the change and corresponding mechanisms of the Beaufort Gyre from the forcing processes.

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Spatial distribution of calcium carbonate saturation state in the surface layer of the Canada Basin in the last decade

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Ocean acidification and calcium carbonate undersaturation are results of the uptake of anthropogenic CO_2. In the Arctic Ocean, calcium carbonate saturation state (Ω) declined rapidly in the early 2000s, which was caused not only by anthropogenic CO_2 accumulation, but also by the effect of melting of sea ice [1]. Here, by using observations from 2007 to 2016, we studied interannual variation and spatial distribution of Ω in the surface layer of the Canada Basin. It was found that undersaturation of Ω didn't grow steadily but slightly rebounded in south-central region of the Canada Basin. It was mainly caused by a decrease in dilution effect, which might be due to the removal of sea ice meltwater to downstream region and deeper layer. In northern region, where dilution effect and air-sea disequilibrium were relatively stable, Ω didn't change significantly. In southwestern region, decreased dilution effect was offset by effect of a decrease in air-sea disequilibrium, which made Ω to not change. However, Ω continuously decreased in the southeastern region, which was owing to the additive effect of increase of dilution and decrease of air-sea disequilibrium.