2017 FAMOS meeting abstracts

Almansi, Mattia: Johns Hopkins University - USA, mattia.almansi@jhu.edu (PhD Student)

Characteristics and causes of Denmark Strait Overflow Water transport variability

The Irminger Basin is dynamically relevant to the global climate system. Indeed, the exchange of freshwater between the east Greenland shelf and the basin is a key element in the maintenance and variability of the Atlantic Meridional Overturning Circulation. Therefore, we have set up a high-resolution realistic model centered on the east Greenland shelf, the Iceland and Irminger Seas to interpret the sparse observations available for this area. The dynamics are simulated using the Massachusetts Institute of Technology general circulation model and results from a 12 month (from September 2007 to September 2008) simulation are presented. The model domain has been extended with respect to a previous version of this model to include the whole Iceland Sea in the north as well as Cape Farewell in the southwest: the regional configuration extends between 47 ◦ W–1 ◦ E and 57 ◦ N–77 ◦ N and the grid resolution over the center of the domain (the east Greenland shelf, the Iceland and Irminger Seas) is 2km with 216 vertical levels. The previous version of this model has also been improved: surface runoff and solid discharge from the Greenland Ice Sheet are now included. Moreover, we have implemented a high-resolution regional reanalysis in order to better represent barrier and katabatic winds. Boluses and pulses are mesoscale features that cross the Denmark Strait increasing the overflow transport. Characteristics and causes of boluses and pulses are investigated by backtracking Lagrangian particles seeded in the Denmark Strait.

Ashjian, Carin: WHOI, cashjian@whoi.edu, Senior Scientist

Mesozooplankton are not herbivores: the importance of microzooplankton in mesozooplankton diets and Arctic and Sub-Arctic trophic linkages

Large copepods, such as Calanus spp., in Arctic regions typically are described as herbivores, although it has been hypothesized that microzooplankton could constitute a significant component of their diet. Nonetheless, the concept of Calanus spp. as herbivores persists in the literature. Grazing experiments conducted in the Bering and Chukchi Seas over several years demonstrated that microzooplankton are important prey for both copepods and euphausiids, with the relative importance of microzooplankton in the diet varying between species and seasons. Microzooplankton were a greater proportion of the copepod diet during summer relative to spring, coincident with a greater proportion of microzooplankton in the available prey field. Microzooplankton were more important prey for the large shelf-slope C. glacialis than to the basin species C. hyperboreus and were greatly preferred over phytoplankton by the strongly omnivorous Metridia spp. at all times of the year. Trophic cascades during grazing experiments could result in significant underestimates of chlorophyll grazing rates by mesozooplankton, especially for those taxa that showed strong preference for microzooplankkon prey. These results further support the growing evidence that most mesozooplankton are not herbivorous, but are omnivorous even during periods of high primary productivity.

Babb, Dave: University of Manitoba – Canada, David.Babb@umanitoba.ca (Research Associate)

Seasonal preconditioning towards younger and thinner sea ice in the Beaufort Sea during winter 2016 and the influence on summer melt

During the 2016 September sea ice minimum the Beaufort Sea became ice-free for the second time in the observational record. Continuing our work from the 2012 sea ice minimum, when the Beaufort Sea became ice free for the first time, we look at how late winter dynamics seasonally preconditioned the ice pack for an early breakup and accelerated ice albedo feedback loop. We focus on a series of storms during late winter that drove easterly winds and caused the ice pack to diverge, thereby creating areas of young ice that preferentially melted out during spring. The young ice promoted the early formation of vast areas of open water within the Beaufort Sea that fostered the early onset of solar heating of the upper ocean. Using a combination of ice charts from the Canadian Ice Service and remotely sensed ice thickness data, we identify the effect these storms had on the ice pack and set the historical context of such preconditioning.

Barton, Benjamin: University of Western Brittany - UK, benjamin.barton@etudiant.univ-brest.fr (PhD Student)

Barents Sea "atlantification" induces frontal constraint on winter ice extent

The Barents Sea has experienced more winter sea ice extent decline than any other Arctic region since 1979. Atlantic Water (AW) entering the Barents Sea is modified by winter convection into Barents Sea Water (BSW) that in turn carries its properties almost unchanged onwards to Denmark Strait. It has been proposed that changes to winter sea ice south of the Barents Sea Polar Front (PF) will affect BSW properties. This study uses sea surface temperature (SST) observations to derive the location of the PF in the eastern Barents Sea, a feature that has mostly eluded observation under seasonal sea ice. The PF is found to be steered along the 220 m isobath at 76.5 °N, and independent of the sea ice edge. Ship-based climatology data reveals the PF divides BSW from Arctic Water (ArW), with salinity gradients across the front dominating the SST gradient impact on density. The PF SST gradient has increased over time, such that winter sea ice has been unable to expand south across it since 2005. Empirical orthogonal function analysis reveals that 47.6 % of the de-seasoned SST variability is correlated (r = 0.65) to sub-surface AW temperature at the Kola section to the west. Following the significant reduction in winter sea ice post-2005 there is a significant 0.06 increase in BSW salinity that can be explained by the loss of sea ice melt water south of the Polar Front. A density increase of 0.03 kg m^-3 is also observed in BSW, equivalent to a 17 % increase in the density from AW to BSW. The implications of the BSW density increase are twofold: BSW will settle at a deeper depth in the Arctic Basin; and the density difference between ArW and BSW in the northern Barents Sea will increase, leading to an increase in the generation of high potential vorticity in BSW and a corresponding increase in the cyclonic circulation of the Eurasian Basin.

Bateson, Adam: University of Reading - UK, a.w.bateson@pgr.reading.ac.uk (PhD Student)

Fragmentation and melting of the seasonal sea ice cover

Recent years have seen a rapid reduction in the summer extent of Arctic sea ice. This trend has implications for navigation, oil exploration, wildlife, and local communities. Furthermore the Arctic sea ice cover impacts the exchange of heat and momentum between the ocean and atmosphere with significant teleconnections across the climate system, particularly mid to low latitudes in the Northern Hemisphere.

The treatment of melting and break-up processes of the seasonal sea ice cover within climate models is currently limited. In particular floes are assumed to have a uniform size which does not evolve with time. Observations suggest however that floe sizes can be modelled as truncated power law distributions, with different exponents for smaller and larger floes.

This study aims to examine factors controlling the floe size distribution in the seasonal and marginal ice zone. This includes lateral melting, wave induced break-up of floes, and the feedback between floe size and the mixed ocean layer. These results are then used to quantify the proximate mechanisms of seasonal sea ice reduction in a sea ice—ocean mixed layer model. Observations are subsequently used to assess and calibrate the model. The preliminary results of these investigations will be presented here.

Bebieva, Yana: Yale University, yana.bebieva@yale.edu, PhD student

Layering in the Arctic Ocean: the interplay between entrainment and fluxes

We explore the physics of double-diffusive layers in the Arctic Ocean through both a theoretical and observational approach. Vertical heat and salt flux divergences plus entrainment at the layer interfaces give rise to well-defined temperature and salinity relationships characterizing these layers. Understanding the interplay between these processes provides insight into the governing physics for a range of double-diffusive processes. We show that at shallower depths in the water column, and for thinner layers, entrainment is more important in setting these relationships. At deeper depths, and for generally thicker layers, vertical heat and salt flux divergences are dominant. Exploring and understanding the reasons for this sheds light on heat transport in the Arctic Ocean as well as the physics of double-diffusive layering in the world's oceans.

Bouchat, Amélie: McGill University - Canada, amelie.bouchat@mail.mcgill.com (PhD Student)

Using RGPS Deformation Fields to Constrain Sea-Ice Mechanical Strength Parameters

We investigate the ability of viscous-plastic (VP) sea-ice models with an elliptical yield curve and normal flow rule to reproduce the shear and divergence distributions derived from the RADARSAT Geophysical Processor System (RGPS). In particular, we reformulate the VP elliptical rheology to allow independent changes in the ice compressive, shear and isotropic tensile strength parameters (P*, S*, T*, respectively) in order to study the sensitivity of the deformation distributions to changes in the ice mechanical strength parameters. Our 10 km VP simulation with standard ice mechanical strength parameters $P^* = 27.5$ kNm^{-2}, $S^* = 6.9$ kNm^{-2}, and $T^* = 0$ kNm^{-2} (ellipse aspect ratio of $e = 2$) does not reproduce the large shear and divergence deformations observed in the RGPS deformation fields, and specifically lacks well-defined, active linear kinematic features (LKFs). Probability density functions (PDFs) for the shear and divergence of are nonetheless not Gaussian. Reducing the ice compressive strength (with constant S* and T*) or increasing the ice shear strength (with constant P* and T*) both results in shear and divergence PDFs in better agreement with RGPS distributions. The isotropic tensile strength of sea ice does not significantly affect the shear and divergence distributions. When considering additional metrics, such as : the ice drift error, mean ice thickness fields, and spatial scaling of the total deformations, our results suggest that reducing the ice compressive strength P* (while keeping S* constant, i.e. reducing the ellipse aspect ratio) is a better solution than increasing the shear strength to improve simulations of the Arctic sea-ice cover with the VP elliptical rheology.

Boutin, Guillaume: IFREMER - France, guillaume.boutin@ifremer.fr (PhD Student)

Coupling a spectral wave model with a coupled ocean-ice model: effects on the ice edge and impact on lateral melting

Sea ice representation in climate models remains incomplete, as different processes are poorly understood, such as the surface wave effects in the marginal ice zone. The modeling of sea ice impact in wave models offers new opportunities to investigate the impact of such interactions. To this end, NEMO-LIM3 has been coupled with the wave model WAVEWATCH III using OASIS-MCT.

WAVEWATCH III includes a sea-ice representation which is expected to apply to a variety of ice conditions with the exception of forming ice. In this model, the ice is treated as a single layer that can be fractured in many floes expected to be equivalent to circular floes with a power law floe size distribution (FSD) that is defined from the maximum diameter Dmax and a fragility parameter. This layer of ice induces a dissipation of the wave energy through basal friction (Stopa et al. The Cryosphere, 2016) and anelastic dissipation associated with ice flexure (Boutin et al., 2017), in addition to an energy-conserving scattering modeled following Kohout and Meylan (2008). Besides the impact on some attenuation processes this break-up is expected to increase the lateral melt (Asplin et al., JGR, 2012) and let the floes drift freely (Williams et al., The Cryosphere, 2017), but such features could not be included in the wave model.

The coupling allows us to send Dmax to NEMO-LIM3, from which the FSD is deduced and advected following Zhang et al. (Ocean Model. 2015). This FSD is then used in the lateral melt computation, and finally sent back to WAVEWATCH III along with the ice concentration and thickness. Furthermore, the wave attenuation is associated with a loss of momentum, resulting in a radiative stress described by Longuet-Higgins (Proc. R. Soc. A., 1977). This stress is computed in WAVEWATCH III and provided to the ice model.

Academic cases are used to discuss the effects of the coupling. The radiative stress pushes the ice in the wave direction of preparation until the concentration exceeds a level for which the internal stress resistance to compression overcomes the stress. The lateral melt achieved with our power law FSD differs substantially from the one achieved with diameters derived from the concentration (Lupkes et al., JGR, 2012).

Brunette, Charles: McGill University - Canada, charles.brunette@mail.mcgill.ca (PhD Student)

Winter coastal divergence as a predictor for the minimum sea ice extent in the Laptev Sea

In addition to its downward trend, the minimum sea ice extent (SIE) displays important interannual variability that represents a challenge in terms of sea ice predictability. Williams et al. [2016] propose winter dynamic preconditioning as a predictor for the pan-Arctic minimum SIE. We study this mechanism at a regional scale and demonstrate feasibility of using late winter coastal divergence as a predictor for the minimum SIE on a seasonal timescale. Following Nikolaeva & Sesterikov [1970], we take the Laptev Sea as a first case of study. We follow motion of sea ice in the winter using the Lagrangian Ice Tracker System (LITS), forced with sea ice drifts from the Polar Pathfinder V3 (Tschudi et al. [2016]). We identify areas of coastal divergence that lead to formation of coastal polynyas. New ice forms in the coastal polynyas during the winter. However, new ice that forms late in the winter does not grow to a sufficient thickness to survive the summer melt. Between February 1st and May 1st, sea ice can freeze up to a thickness of 1 to 1.5m on average, which is equivalent to climatological summer melt (Nikolaeva & Sesterikov [1970]). Consequently, anomalies of late winter coastal divergence are associated to anomalies of the following September minimum SIE, i.e. the more late winter coastal divergence, the less sea ice in September. In the Laptev Sea, the strongest negative correlation is obtained when considering coastal divergence occurring between February and May (r=-0.63). Also, a slope of m=-3 is present between anomalies of coastal divergence and minimum SIE, indicating that sea ice states anomalies at the end of the winter are amplified through the melt season.

Bushuk, Mitchel: Geophysical Fluid Dynamics Laborary, mitchell.bushuk@noaa.gov, Research Scientist

Regional Arctic sea-ice prediction: A direct comparison of potential versus operational seasonal forecast skill

Seasonal predictions of Arctic sea ice on regional spatial scales are a pressing need for a broad group of stakeholders, however, most forecast skill assessments to date have focused on pan-Arctic sea-ice extent (SIE). In this work, we present a direct comparison of potential and operational seasonal prediction skill for regional Arctic SIE. This assessment is based on two complementary suites of seasonal prediction ensemble experiments performed with a global coupled climate model. First, we assess the operational prediction skill for detrended regional SIE using a suite of retrospective initialized seasonal forecasts spanning 1980-2017. These retrospective forecasts are found to skillfully predict regional winter SIE at lead times of 3-11 months and regional summer SIE at lead times of 1-4 months, owing partially to subsurface ocean temperature and sea-ice thickness initial conditions, respectively. Second, we present a suite of perfect model predictability experiments with start dates spanning the calendar year, which are used to quantity the potential regional prediction skill of this system. These perfect model experiments reveal that regional Arctic SIE is potentially predictable at lead times beyond 12 months in many regions, substantially longer than the current operational skill of this system. Both the retrospective forecasts and perfect model experiments display a spring prediction skill barrier for regional summer SIE forecasts, indicating a fundamental predictability limit for summer regional predictions. The skill gap identified in this work indicates a promising potential for future improvements in regional SIE predictions.

Castellani, Giulia: Alfred Wegener Institute (AWI), giulia.castellani@awi.de

Multi-decadal simulation of Arctic sea-ice algae: what can we learn from the past?

Algae growing in sea ice represent a source of carbon for sympagic and pelagic ecosystems. The biophysical habitat of sea ice on large scales and the physical drivers of algae phenology are key to understanding Arctic ecosystem dynamics. Changes in sea ice affect the spatial distribution of sea-ice algae and time of bloom onset. Mainly in a time of great changes, understanding sea-ice algae phenology and their response to changes in the biophysical habitat of sea ice over the last decades are fundamental for predicting ecosystems response to ongoing Arctic climate change. In the present work we show pan-Arctic results obtained from a new Sea Ice Model for Bottom Algae (SIMBA) coupled with a 3D sea-ice–ocean model. A one year test simulation shows that, when nutrients are not limited, the algal bloom is triggered by light, and shows a latitudinal dependency. Snow and ice also play a key role in ice algal growth. Simulations show that after the spring bloom, algae are nutrient-limited before the end of summer and finally they leave the ice habitat during ice melt. SIMBA is run from 1979 to 2013 to investigate changes in bloom onset, day of bloom peak, maximum biomass and length of the bloom. Bloom onset, peak and length show a large interannual variability. An earlier onset of the bloom corresponds to longer blooming period and a larger maximum biomass, resulting in a longer thriving season for sympagic and pelagic species and larger food availability. The main driving factor of the interannual variability is represented by nutrients, pointing to the need of properly model the nutrients fluxes at the ice-ocean interface.

Castro de la Guardia, Laura: University of Alberta, castrode@ualberta.ca

Evaluating the importance of nutrient sources to primary production in the Arctic, a high resolution modelling experiment using BLINGv0-NEMO-LIM2 framework.

BLING (Biogeochemestry with Light, Iron, Nutrient, and Gases) is a biogeochemical model that empirically calculates community production and explicitly simulates the biogeochemical cycles of oxygen (O), phosphate (P), iron (Fe) and inorganic carbon (C). The growth formulation is based on a mixed Monod-quota scheme, specifically, a in-cell fixed Redfield stoichiometry of C/P, but using a variable Fe quota. Ocean productivity and phytoplankton growth are limited by the ambient macro-nutrient concentrations, light, temperature and the internal availability of Fe. Iron also limits the light harvesting capacity of phytoplankton, and slows down photosynthesis if in low quantities. BLINGv0 can be used with either regional or global configurations of NEMO, at both high or low resolution. Here, we run BLINGv0 coupled to a regional configuration of NEMO at a 0.25 degree resolution. We integrate for 56 years (1958-2014) to evaluate the solution. We then set-up sensitivity experiments to test the role of nutrient sources like the inflow from Bering Strait, river runoff and sea ice, on the primary production throughout the Arctic.

Chanona, Melanie: University of British Columbia - Canada, mchanona@eoas.ubc.ca (PhD Student)

Variability of internal wave-driven dissipation, diffusivity, and stratification in the Canadian Arctic Ocean

To better assess the risks associated with evolving Arctic Ocean wave energy budgets, we have completed a widespread survey of internal wave energy and evaluated its potential for generating turbulent mixing in the Canadian Arctic Ocean. Historically, the Arctic Ocean's unique density structure has acted as a barrier to the upward mixing of heat contained in deep, warm Atlantic-sourced water, thus effectively isolating the surface sea-ice pack from ocean heat fluxes. However, there are growing concerns that increasing internal wave energy in the Arctic Ocean could enhance vertical mixing rates and erode this stratification barrier.

Using over 2800 CTD profiles collected in the Canadian Arctic Ocean from 2002-2015, we estimate the turbulent mixing that we expect to result from internal wave breaking by first calculating the strain associated with vertical isopycnal displacements. We then apply a finescale parameterization to estimate the associated turbulent dissipation rate. We further investigate variability in stratification strength and evaluate its role in suppressing or enhancing potential mixing hot spots. The varying contributions of turbulent dissipation and stratification to the resulting mixing rate reveal distinct geographic patterns. These patterns provide insight into regions where local turbulence is capable of generating enhanced turbulent heat fluxes, which may contribute to elevated risks of sea ice loss. We also observe wide localized time variability, with wave-driven mixing rates spanning up to four orders of magnitude. There is no clear evidence of seasonal or inter-annual trends. We believe the extensive scope of these inferred internal-wave driven diffusivities, in time, depth and regionally, can help inform Arctic Ocean modelling efforts, particularly by helping to alleviate the challenges associated with mixing patchiness and limited microstructure measurements.

Chen, Xianyao: Ocean University of China - China, chenxy@ouc.edu.cn (Professor)

Arctic Sea Level Variability: Observations and Simulations

Arctic sea level rising is studied using tide gauge stations, satellite altimeter observations, GRACE satellite, and the ocean reanalysis datasets. It is shown that the main sea level rise in the Arctic area is dominated by the global averaged mass change, which matches the recent analysis on the global mass-equivalent sea level rise at a rate about 1 - 2 mm/yr from 1993-2014. But the regional homogeneous mass increase did not have dynamical contribution to the freshwater output through the FRAM strait. The observational dataset and reanalysis dataset show that this is controlled by the surface atmospheric variability on both inter annual and interdecadal time scales, and modulated by the steric sea level change.

Cornish, Sam: University of Oxford - UK, sam.cornish@univ.ox.ac.uk (PhD Student)

Response of Arctic freshwater to a step change in atmospheric circulation across the CMIP5 ensemble

The relationship between freshwater content in the Arctic and atmospheric circulation is a major uncertainty in climate predictions. Theory suggests that Ekman convergence associated with anticyclonic wind stress over the Beaufort Sea builds a freshwater lens, a process balanced by eddy fluxes. A finer understanding of the magnitude and timescale of freshwater response to different modes of atmospheric variability is lacking, however. We take a computationally efficient approach to interrogate this relationship in CMIP5 coupled climate models, by using multiple linear lagged regression to calculate the freshwater response to a hypothetical step change in atmospheric forcing in unperturbed control runs. Given that most Arctic freshwater is stored in the Beaufort Gyre, the amplitude and timescale of freshwater response provides a window into the dynamics governing its adjustment. Furthermore, the step-response function can also be convolved with a given timeseries of atmospheric forcing to predict or hindcast the freshwater response.

Dukhovskoy, Dmitry: COAPS FSU - USA, ddukhovskoy@fsu.edu (Associate Scientist)

Freshwater pathways in the Arctic Ocean and North Atlantic from numerical experiments with passive tracers

The freshwater budget of the Arctic Ocean has been increased over the last two decades. The largest increase of freshwater content is observed in the Beaufort Gyre. Contributions from the major freshwater sources to the Beaufort Gyre freshwater budget are not well known yet. The main reason for this is lack of knowledge about pathways of freshwater from the major sources. This study is motivated by the need to better understand, characterize, and quantify contributions from different freshwater sources to the Arctic Ocean freshwater budget. The study employs a coupled 0.08-degree Arctic Ocean Hybrid Coordinate Ocean Model (HYCOM) and Los Alamos sea ice code (CICE) modeling system (AO HYCOM-CICE). The model is run for 1993-2015 forced by the 0.08-degree Global HYCOM reanalysis at the lateral open boundaries and CFSR atmospheric fields at the surface. During the simulation, five passive tracers are constantly released at the major freshwater sources: along the Greenland coast, Mackenzie River, East Eurasian Rivers (the East-Siberian and Laptev Seas), West Eurasian Rivers (the Kara, Barents, and White Seas), and the Bering Strait. The amount of tracers fluxed into the ocean is set proportional to the freshwater flux at the sources. The presentation shows preliminary results from the simulation. Freshwater pathways and their variability is discussed. Contributions of the freshwater sources to the Beaufort Gyre budget are analyzed.

Dupont, Frederic: ECCC, frederic.dupont@canada.ca

Improving the representation of grounded ridges in the Lemieux et al. (2015) landfast ice parametrization and other considerations concerning the statistical representation of drag on ice

Lemieux et al. (2015) introduced a simple and efficient way of representing landfast ice in numerical models of sea-ice. It is now used operationally in Canadian ice-ocean short-term forecasting models. We propose herein extensions of this representation that duly takes into account the ice thickness distribution of present-day models. This leads as well to considerations about the representation of form drag using a statistical approach. Moreover, it appears as well that the drag between by ridges and the ocean should include the explicit treatment of the penetration of ridges into the oceanic vertical coordinate system.

Fedorov, Alexey: Yale University - USA, alexey.fedorov@yale.edu (Professor)

Can Arctic sea ice decline drive a slow-down of the Atlantic meridional overturning circulation?

The ongoing decline of Arctic sea ice exposes the ocean to anomalous surface heat and freshwater fluxes, resulting in positive buoyancy anomalies that can affect ocean circulation. In this study, we use an optimal flux perturbation framework and comprehensive climate model simulations to estimate the sensitivity of the Atlantic meridional overturning circulation (AMOC) to such buoyancy forcing over the Arctic and globally, and more generally to sea ice decline. We find that on decadal timescales anomalies over the subpolar North Atlantic have the largest impact on the AMOC, while on multi-decadal timescales (longer than 20 years), anomalies in the Arctic become more important. While spreading from the Arctic to the North Atlantic, these positive buoyancy anomalies suppress deep convection and weaken the AMOC and its poleward heat transport. Consequently, the Arctic sea ice decline may explain the suggested slow-down of the AMOC and the “Warming Hole” that persists in the subpolar North Atlantic. A further analysis using the CMIP5 data confirm that the remote control of the AMOC intensity and heat transport from the Arctic is indeed a robust feature of model simulations on multi-decadal timescales.

Feng, Zhixuan: WHOI - USA, zfeng@whoi.edu (Postdoc)

Pelagic-benthic coupling processes in the St. Lawrence Island Polynya region, northern Bering Sea: modeling and observational Synthesis

The Pacific Arctic Ocean is experiencing significant changes in atmosphere, sea ice, and ocean that may alter the marine ecosystem. The St. Lawrence Island Polynya (SLIP) region is one of the largest polynyas in the Northern Hemisphere. This shallow continental shelf polynya is widely known as an ecological hotspot in the Arctic where highly productive benthic communities provide abundant prey for benthic-feeding mammals and seabirds, particularly endangered spectacled eiders. Observational data have suggested interesting spatial patterns (e.g. the west-east asymmetry in sediment chlorophyll content and benthic macrofaunal biomass), along with a general declining trend in the percent biomass of medium-sized nuculanid bivalves since 1980s. To better understand the coupled physical and biological processes that drive the temporal variability and spatial heterogeneity, we synthesized 17 years (1998-2014) of satellite-retrieved sea ice and chlorophyll concentrations, long-term benthic observations, and an ice-ocean-biogeochemical coupled model. Despite substantial inter-annual variability in sea ice retreat and pelagic bloom peak timing, a high synchronicity between the two events exists over the western side of the polynya but not over the eastern side that may explain the observed west-east asymmetry in sediment chlorophyll content and benthic macrofaunal biomass. A higher ice-bloom synchronicity in the west could lead to a greater amount of biogenic production being exported directly to the benthos. Associations between the west-east asymmetry and the prevailing northerly to easterly winds, the location and timing of polynya formation, and the distribution of high-nutrient Anadyr Water are explored through diagnosis of the ice-ocean-biogeochemical model. This analysis of the coupled physical-biological processes will facilitate prediction of the persistence or relocation of benthic hotspots and the development of management strategies to mitigate detrimental effects from climate change in the Pacific Arctic Ocean.

Feucher, Charlène: University of Alberta - Canada, feucher@ualberta.ca (Postdoc)

Labrador Sea Water formation rate and its impact on the Meridional Overturning Circulation

The meridional overturning circulation (MOC) is a key component of the Earth's climate system as it contributes to the redistribution of heat, salt and anthropogenic carbon in the world ocean. The lower limb of the MOC is associated with dense water formation driven by buoyancy forcing and is carried by a vigorous deep western boundary current (DWBC). The main water mass in the subpolar North Atlantic is the North Atlantic Deep Water (NADW) and its lightest contribution is the Labrador Sea Water (LSW). The LSW is formed in the Labrador Sea through deep wintertime ocean convection. After its formation, the LSW is exported out of the basin via the DWBC. Changes in the deep water formation have direct consequences for the ventilation of the deep ocean and its capability to store anthropogenic carbon, as well as for the strength of the MOC and the associated heat transport. Many numerical studies have shown a link between the LSW formation rate and the strength of the MOC. However, the impact of the formation of the LSW on the MOC remains unclear and is still under debate. In this study, we will analyze the change in the fate of the LSW formation and how it impacts the MOC. Change in the DWBC associated with change in the LSW formation rate will be investigated. The formation rate of the LSW will be computed using an instantaneous kinematic subduction approach by analyzing the vertical transport of a water mass through the base of the instantaneous mixed layer. We will address the impact of the Labrador Sea Water on the MOC over the time period from 2002 to 2016 using simulations from the DRAKKAR project, especially a 1⁄4 degree Arctic and Northern Hemisphere Atlantic (ANHA) configuration and an eddy-permitting 1/12 degree ANHA configuration.

Fujisaki-Manome, Ayumi: University of Michigan, ayumif@umich.edu, Assistant Research Scientist

Impacts of shelf-basin exchange on water properties in the East Siberian Sea shelf seen in a historical ice-ocean simulation

The East Siberian Sea shelf is characterized by unique features of being the widest of the Arctic Ocean shelf seas, the active biogeochemical environment, and significant amounts of gas hydrate stored in subsea permafrost. Shelf-basin exchange and associated intrusion of the warmer Atlantic Water, induced by upwind-favorable winds, are likely key factors to affect water properties, biogeochemical activity, and the stability of gas hydrate in subsea permafrost. This study examines shelf-basin exchange induced by shelf-break upwelling and its impacts on water properties in the East Siberian Sea shelf, based on a historical ice-ocean simulation using the Princeton Ocean Model coupled with an ice model.

Garcia Quintana, Yarisbel: University of Alberta - Canada, yarisbel@ualberta.ca (PhD Student)

Transformation of Atlantic Water in the Nordic Seas and its role on driving the North Icelandic Jet

The Nordic Seas (NS) are the main gateway between the Arctic and the Atlantic Oceans. The basin can be considered as the headwaters for the Meridional Overturning Circulation (MOC), for it is there that the Denmark Strait Overflow Water (DSOW) and the Iceland-Scotland Overflow Water (ISOW) acquire their properties. Lately, lots of attention is been given to the sources of DSOW, specially to the North Icelandic Jet (NIJ). The NIJ accounts for 28% of the observed overflow transport and is been confirmed to be the its densest contribution. Unfortunately, it is still not certain the possesses behind the formation of the NIJ. Here we explore the transformation of the Atlantic Water (AW) as it enters the NS through Denmark Strait within the North Iceland Irminger Current (NIIC), and its contribution to the NIJ. To do so, we use an eddy-permitting ocean general circulation model run over the period 2002 to 2016. Two different approaches are used to track the AW transformation in the NS: the well-tested off-line Lagrangian tool ARIANE and on-line passive tracers. The same definition for AW was used in both cases. The passive tracer analysis shows a major AW inflow into the Nordic Seas occurring through Iceland Faroe Ridge and Faroe Scotland Channel, and a higher tracer concentration in the eastern rim of the Nordic Seas. The Ariane trajectories show that 34% of the AW entering and leaving the NS through DS, is transformed in the rim current overturning loop to $\sigma \geq 27.93$ kg/m3 within less than 6 years. Most important, 30% of the AW inflowing within the NIIC transforms, to $\sigma \geq 27.93$ kg/m3 north of Iceland to form the NIJ, and contributing to the DSOW within less than 1 year.

Gelderloos, Renske: John Hopkins University - USA, rgelder2@jhu.edu (Assistant Research Scientist)

Impact of Beaufort High anomalies on Arctic shipping routes

Sea ice cover in the Arctic has decreased rapidly over the past decades. Though the trend is clear, interannual variability is large, and the spatial patterns differ markedly from one year to the next. One of the factors impacting this spatial pattern is the strength of the high-pressure system over the Beaufort Sea. We have run a suite of numerical simulations across different groups in different models, all with the same perturbation in Beaufort Sea pressure: a step function increasing or decreasing the pressure, respectively. The response is consistent across models: A more intense Beaufort High increases sea ice thickness in the Canadian Arctic Archipelago along the Northwest Passage, while a less intense Beaufort High increases the sea ice thickness in the Bering Strait, the Chukchi Sea and the East Siberian Sea, along the Northern Sea Route. The changes are large driven by anomalies ice transport. We compare these model results with a composite of satellite observation of ice drift velocities and thickness to assess how large the impact is in the real world, and use the Arctic Climate Response Function framework to make predictions for the future.

Holdsworth, Amber: Department of Fisheries and Oceans Canada - Canada,
Amber.Holdsworth@dfo-mpo.gc.ca (Physical Scientist)

The Influence of Arctic Climate Change on Local Marine Ecology

The Arctic is changing rapidly as a result of global climate change. These changes can influence the biology and chemistry of the ocean including ocean acidification, nutrient stratification, as well as changes in phytoplankton and zooplankton abundance. To project changing oceanic conditions under future climate change scenarios we are developing a regional model of the Arctic using the Nucleus for European Modelling of the Ocean (NEMO 3.6) model. The model features the Canadian Ocean Ecosystem Model (CanOE) and the Louvain-la-Neuve sea-ice model (LIM3) as well as improved model bathymetry from the Canadian Hydrographic Survey. The 1/4 degree regional model will feature two high resolution nests developed using adaptive grid refinement in Fortran (AGRIF): one at Cambridge Bay and the other in the Inuvialuit Settlement Region. Existing observations from within these subdomains will be used to validate model performance. Using links between physics and biology this new model will be used to project changes under future climate change scenarios and to drive higher trophic level models.

Hu, Xianmin: University of Alberta, pmyers@ualberta.ca

Pacific Water Pathway in the Arctic Ocean Revealed by Online Passive Tracer in NEMO Simulations

Pacific Water inflow through the Bering Strait plays an important role in the Arctic Ocean. Besides the Atlantic water, Pacific Water is the other major source water that mixes and forms the water masses in the Arctic Ocean. As the Pacific Water brings large amount of heat and freshwater into the Arctic Ocean, its pathway is essential for understanding the Arctic Ocean sea ice condition, stratification (particularly within the upper layer), circulation as well as biochemical tracer distribution.

Hutter, Nils: AWI - Germany, nils.hutter@awi.de (PhD Student)

Developing a dataset of Linear Kinematic Features (LKFs) for the evaluation of small-scale sea ice deformation

The Arctic sea ice deforms constantly due to stresses imposed by winds, ocean currents and interaction with coastlines. The most dominant features produced by this deformation in the ice cover are leads and pressure ridges that are often referred to as Linear Kinematic Features (LKFs). 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, scaling properties of sea-ice deformation are commonly used to evaluate the modelled LKFs, besides other measures like lead area density. These metrics evade the problem of detecting individual LKFs by taking statistics over continuous fields like sea ice deformation or concentration. This way, they can provide specific information, but lack a comprehensive description of LKFs.
We detect individual LKFs in sea ice deformation fields from satellite observations with an object detection algorithm. Combining this information with the sea ice drift fields used to derive the deformation fields, the LKFs are tracked in time. In doing so, the spatial characteristics (density, length, orientation, intersection angle, curvature) as well as the temporal evolution can be extracted from the same data-set. This algorithm can be applied to modelled sea-ice deformation and drift to enable a consistent comparison and thorough evaluation of simulated sea-ice deformation. We present preliminary results of LKFs detected in the RGPS data set and give examples of possible applications.

Ilicak, Mehmet: Uni Research, BCCR, Norway, Uni Research, BCCR, Norway

Possible impact of thermobaricity in the Arctic Ocean

In this study, we investigate possible sea ice decrease due to thermobaricity in the Arctic Ocean. We test our hypothesis in an idealized convection setup. We conduct high resolution large eddy simulations (LES) of idealized Arctic Ocean profiles using current observations and idealized warming scenarios. We find that if the warm Atlantic Layer brings also more saline water into the Arctic, thermobaricity can occur in the interior of the Arctic. This leads to bring the warm water to surface and melts the sea ice.

Itkin, Polona: Norwegian Polar Institute - Norway, Polona.Itkin@npolar.no (Postdoc)

Direct observations of atmosphere – sea ice – ocean interactions during Arctic winter and spring storms

To study the thinner and younger sea ice that now dominates the Arctic the Norwegian Young Sea ICE expedition (N-ICE2015) was launched in the ice-covered region north of Svalbard, from January to June 2015. During this time, eight local and remote storms affected the region and rare direct observations of the atmosphere, snow, ice and ocean were conducted. Six of these winter storms passed directly over the expedition and resulted in air temperatures rising from below –30oC to near 0oC, followed by abrupt cooling. Substantial snowfall prior to the campaign had already formed a snow pack of approximately 50 cm, to which the February storms contributed an additional 6 cm. The deep snow layer effectively isolated the ice cover and prevented bottom ice growth resulting in low brine fluxes. Peak wind speeds during winter storms exceeded 20 m/s, causing strong snow re-distribution, release of sea salt aerosol and sea ice deformation. The heavy snow load caused widespread negative freeboard; during sea ice deformation events, level ice floes were flooded by sea water, and at least 6-10 cm snow-ice layer was formed. Elevated deformation rates during the most powerful winter storms damaged the ice cover permanently such that the response to wind forcing increased by 60 %. As a result of a remote storm in April deformation processes opened about 4 % of the total area into leads with open water, while a similar amount of ice was deformed into pressure ridges. The strong winds also enhanced ocean mixing and increased ocean heat fluxes three-fold in the pycnocline from 4 to 12 W/m2. Ocean heat fluxes were extremely large (over 300 W/m2) during storms in regions where the warm Atlantic inflow is located close to surface over shallow topography. This resulted in very large (5-25 cm/day) bottom ice melt and in cases flooding due to heavy snow load. Storm events increased the carbon dioxide exchange between the atmosphere and ocean but also affected the pCO2 in surface waters through mixing. Finally, the combination of a higher lead fraction and thinner ice cover, driven in part by storms, helped facilitate an early under-ice phytoplankton bloom in May, far inside the ice pack. In summary the storms entail significant effects on the ice pack that may last much longer than the short-lived storm events.

Jin, Meibing: University of Alaska Fairbanks - USA, mjin@alaska.edu (Research Professor)

Effects of model resolution and vertical mixing on the ice-ocean physical and biogeochemical simulations in the Regional Arctic System Model (RASM)

The arctic ecosystem is undergoing rapid changes according to observations and model projections. The current coarse-resolution global Community Earth System Model (CESM) can reproduce major and large-scale patterns but is still missing some key features in the Arctic Ocean, e.g. low surface nutrients in the Canada Basin. To investigate model deficiencies, we incorporated the sea ice and ocean ecosystem modules into the Regional Arctic System Model (RASM), and compared two ice-ocean simulations: 1) R9km: pan-Arctic limited area RASM at 1/12-degree (~9km) resolution and 2) R1deg: global CESM at 1-degree (about 40~60 km in the Arctic) resolution. The two simulations revealed similar results for the Arctic in many comparisons with field and remotely sensed observations, but the R9km demonstrated improved timing and magnitude of the ice algal and phytoplankton blooms and smaller errors in most biophysical variables: ice extent, ice thickness, salinity, and nitrate and chlorophyll concentrations in the Bering Sea and Arctic Ocean. The R9km also showed significant improvement of modeled sea surface nitrate concentrations in the Arctic Basin relative to R1deg. The reduction of nitrate concentration bias is attributed to two factors: Firstly, R9km has higher spatial resolution and can better resolve the sharp gradients along the Beaufort Sea. The coarser resolution R1deg cannot and this causes excessive horizontal mixing and advection of nutrients from the Chukchi Sea into the Canada Basin. The second reason is the implementation of the sub-grid scale brine rejection parameterization, which greatly reduces the model bias of deeper winter mixed layer depth in the Arctic Basin. We note, however, that there are a number of differences in the ice-ocean physics between the two models that contribute to the result. Altogether, higher resolution model improves the simulated phytoplankton bloom timing and chlorophyll concentration, especially in the shelf break and narrow strait regions, but shows only small changes in the Arctic Basin where the phytoplankton bloom is still controlled by light limitation under the current state of ice cover; this light control may become less important as the arctic sea ice cover is further reduced by future climate warming.

Katlein, Christian: AWI - Germany, ckatlein@awi.de (Scientist)

Seasonal evolution of light transmission through Central Arctic sea ice

Light transmission through sea ice has been identified as a critical process for energy partitioning at the polar atmosphere-ice-ocean boundary. Transmission of sunlight influences direct sea ice melting by absorption, heat deposition in the upper ocean, and in particular primary productivity. While earlier observations relied on a limited number of point observations, the recent years have seen an increase in spatially distributed light measurements underneath sea ice using remotely operated vehicles. These measurements allow us to reconstruct the seasonal evolution of the spatial variability in light transmission.
Here we present measurements of sea ice light transmittance from 6 years of polar ROV operations. The dataset covers the entire melt cycle of Central Arctic sea ice. This data from multiple years is combined into a pseudo timeseries describing the seasonal evolution of the changing spatial variability of sea ice optical properties. Snow melt in spring increases light transmission continuously, until a secondary mode originating from translucent melt-ponds appears in the histograms of light transmittance. This secondary mode persists long into autumn, before snow fall reduces overall light levels again. Comparison to several autonomous time series measurements from single locations confirms the detected general patterns of the seasonal evolution of light transmittance variability. These results will allow further insights on the validity of radiation transfer parameterization used in ice-ocean models.

Kazlova, Aliaksandra: University of Bremen, kazlova@uni-bremen.de, PhD student

Changes in Arctic sea ice dynamics observed from SAR satellites (RADARSAT and ANVISAT datasets)

Arctic sea ice is a key element of the climate system, which has a great impact on the regional climate in the mid-latitudes in Eurasia and Northern America and the global climate. An increase in Arctic sea ice speed during recent decades by 10-15% per decade has been observed from buy and satellite observations. There is an evidence from buoys that also the deformation of sea ice has changed. The high spatial resolution of Synthetic Aperture Radar (SAR) observations are best suited for space-borne sea ice deformation retrieval, but they were not yet fully analysed for long-term ice deformation changes. How much the different components in the sea ice force balance have contributed to the observed changes in sea ice dynamics is not fully understood. In order to model sea ice dynamics correctly, these changes over time have to be represented in the model. For example, the sea ice rheology should represent sea ice deformation patterns accurately.

Sea ice motion fields from SAR observations can be used to obtain sea ice strain rates, i.e., sea ice deformation fields. Currently, there is no SAR satellite sea ice deformation datasets covering the complete Arctic Basin available. The RADARSAT RGPS data is mainly covering the Canadian Basin and Beaufort Sea (November 1996 – April 2014) and the ENVISAT dataset, mainly covers the European Arctic region (January 2007 – April 2012). Recently, with the launches of Sentinel -1a and b dataset got much more extensive. Available SAR datasets of sea ice drift and deformation are analysed for changes in space and time (e.g., trend patterns). Findings will contribute to better quantify the changes in Arctic sea ice dynamics and can be used to evaluate sea-ice models.

Kenigson, Jessica: University of Colorado Boulder, jessica.kenigson@colorado.edu, Graduate Research Assistant

A Simple Adiabatic Model for Vertical Variation of Halocline Slope in the Beaufort Gyre

by Jessica Kenigson, Renske Gelderloos, Georgy Manucharyan

The Beaufort Gyre acts as a large fresh water storage reservoir in the Arctic Ocean. The predominantly anticyclonic wind stress curl drives a halocline deepening through Ekman pumping, which has increased since the beginning of this century. A change in prevailing wind conditions could release a large amount of fresh water into the Atlantic Ocean, with significant impacts on the global ocean circulation. However, the processes which determine the shape of the halocline are still poorly understood, which impedes reliable predictions. Prior studies have hypothesized that the basic balance is between steepening of the halocline slope due to Ekman pumping and restoring due to the local formation of mesoscale eddies. The key gyre characteristics then equilibrate on a timescale T ~ 1/K, where K represents the eddy diffusivity. In climate models, K is typically taken to be a constant or an increasing function of the isohaline slope; yet observations of the Beaufort Gyre suggest that the isohaline slope increases with depth, while the along-isopycnal eddy diffusivity decreases from around 750 m2 s-1 at 50 m to 150 m2 s-1 at 600 m. Are observations inadequate to constrain the eddy diffusivity or is theory in need of revision?

In this study, we construct a simple three-layer model of the Beaufort Gyre halocline which extends prior formulations to include the vertical variation of the halocline slope and K. By calculating the profile of K online (through the stability properties of the geostrophic currents) we are able to predict the observed vertical profiles of K, isohaline slope, and geostrophic velocity within the gyre, thereby reconciling the seemingly contradictory observations of K and isohaline slope and improving understanding of the vertical structure of the halocline and eddies. Therefore, climate models should use caution in assuming a simple form of eddy diffusivity which is proportional to isohaline/isopycnal slope. In addition, improved observations of eddy dynamics are needed to constrain the isohaline slope in the Beaufort Gyre and to predict its time evolution.

Kelly, Stephen: University of Southampton - UK, s.kelly@soton.ac.uk (PhD Student)

High-Resolution Modelling of Arctic Circulation Pathways: Applications for the Understanding the Advection of Pollutants

High resolution ocean models allow for a better understanding of the advective pathways in the Arctic Ocean. Studying these pathways has many applications, including modelling the fate of pollutants in the Arctic. There are many potential sources for Arctic pollutants, particularly in a warming climate. With the retreat of sea ice fuelling increased interest in utilising the Arctic for commercial shipping and drilling for fossil fuels, the risk from oil leaks and spills is increasing. Additionally, several major rivers drain into the Arctic Ocean, many of which pass through industrialised areas upstream. This brings with it another potential source of pollutants entering the ocean.

In any case, understanding the long-term fate of these pollutants is important, and understanding the advective pathways in the Arctic is essential for modelling where they will go. Previous work has demonstrated that resolving eddies is necessary for accurately describing the circulation in the Arctic Ocean. Here, we use the 1/12 degree resolution NEMO (Nucleus for European Modelling of the Ocean) model in conjunction with Lagrangian particle tracking software to investigate where pollutants will go, how long they are likely to remain in the Arctic for, and what the uncertainties and variabilities associated with their pathways are. The physical mechanisms driving this variability are also explored.

Additionally, validation work for the leading-edge 1/12 degree version of NEMO is presented. This version of NEMO has undergone extensive global validation, and other work has investigated the model's performance in different regions of the Arctic. Here, NEMO output is compared with satellite derived observational data (e.g. sea ice cover, sea surface height) in order to verify its accuracy on a pan-Arctic scale.

Kovacs, Tamas: AWI - Germany, tamas.kovacs@awi.de (PhD Student)

Climate response functions of the joint freshwater budget of the Arctic and North Atlantic oceans to changes in external wind forcing in an otherwise fully coupled earth system model

Ocean currents conveying large volumes of water can transport heat to great distances, through which they influence the climate. This is particularly true for the Arctic and the North Atlantic, the regions where water circulation has a significant impact on the atmosphere as well as on key oceanic processes. These processes are often sensitive to density stratification of ocean water, which is greatly shaped by salinity, or in another measure, by freshwater storage. Freshwater in the oceans is thus of particular importance.

Being connected by a network of currents, the Arctic and North Atlantic oceans exchange a large volume of water of different characteristics. As a consequence, their freshwater budgets are also connected. However, these budgets show spatial and temporal variations, and the fluxes between them cannot be considered constant either. The freshwater system of the Arctic linked to the North Atlantic is dynamic with changes and anomalies on different time scales, and the changes of this joint system seem to follow the evolution of atmospheric forcing patterns. Previous modeling results suggest the importance of wind stress forcing over key regions such as the Beaufort Sea or the Greenland Sea in influencing the distribution of freshwater.

In this study we examine the reaction of this linked freshwater system to changes in wind stress forcing through numerical experiments using the Modini-system, a partial coupling technique that allows flexible experiments with prescribed wind stress fields for the ocean in the otherwise fully coupled Earth System Model of the Max Planck Institute. The aim of this work is to investigate the role of atmospheric forcing in shaping freshwater reservoirs and exchanges between different subregions of the Arctic and North Atlantic oceans by calculating and analyzing climate response functions to changes in wind forcing over key regions.

Kozlov, Igor: Russian State Hydrometeorological University - Russia, igor.eko@gmail.com (Research Scientist)

Spaceborne SAR observations of small-scale eddies near Svalbard

Authors: I. Kozlov (1, 2), L. Petrenko (2)

Affiliations: 1. Russian State Hydrometeorological University, Russia 2. Marine Hydrophysical Institute of RAS, Russia.

Here we present the results of satellite observations of small-scale eddies (SE) in the Fram Strait and around Svalbard. The study is based on analysis of ENVISAT Advanced Synthetic Aperture Radar (SAR) images acquired in summer 2007. Detailed maps of eddies' locations, diameters and vorticity sign are presented and discussed.

This work is supported by RFBR grant 16-29-02106 mol_a_dk and the Federal Agency for Scientific Organizations Project No. 0827-2014-0011. ENVISAT ASAR data used in this study were provided by the European Space Agency (ESA) through Cat-1 Project C1F-29721.

Kozlov, Igor: Russian State Hydrometeorological University - Russia, igor.eko@gmail.com (Research Scientist)

Linking internal solitary waves and mixing in the Arctic Ocean

Authors: Igor Kozlov (1), E. Zubkova (1), T. Rippeth (2), M. Green (2), B. Lincoln (2), V. Kudryavtsev (1)
Affiliations: 1. Russian State Hydrometeorological University, Russia 2. Bangor University, UK

The results of internal solitary wave (SIW) observations in spaceborne synthetic aperture radar (SAR) images acquired over the ice-free Arctic Ocean in summer 2007 and 2011 are presented. Comparison of satellite-derived probability of ISWs with the model field of barotropic-to-baroclinic energy conversion shows a good agreement between these two quantities for the Eastern Arctic Ocean. Positive correlation is also obtained between ISW probability and the rate of TKE dissipation derived from microstructure observations over the continental slope, suggesting that internal solitary waves may promote enhanced vertical mixing in these regions. Preliminary results of ISW observations in the Arctic Ocean's Canada Basin are also presented. This work is supported by RFBR grants 16-29-02106 mol_a_dk and the Ministry of Education and Science of the Russian Federation President grant MK-5562.2016.5. ENVISAT ASAR data used in this study were provided by the European Space Agency (ESA) through Cat-1 Project C1F-29721.

Kvile, Kristina: WHOI - USA, kkvile@whoi.edu (Postdoc)

Is *Calanus hyperboreus* an expatriate in the Arctic basins?

The copepod *Calanus hyperboreus* is an important link between microplankton and animals at higher trophic levels in the Arctic. The species is commonly described as endemic to the Arctic Ocean basins, and its large lipid reserves, plastic life-span and ability to spawn based on internal lipid reserves are considered adaptations to the unpredictable growth conditions of the Arctic Ocean. However, there is conflicting evidence on whether *C. hyperboreus* is a true Arctic Ocean endemic, or rather an expatriate from surrounding areas. In this study, we investigate this question by (1) mapping the species' spatial distribution from compiled pan-Arctic data, and (2) estimating potential origins of individuals observed within the Arctic Ocean basins using backward-in-time particle tracking coupled with an Arctic ice-ocean model. The mapped distributions indicate that while *C. hyperboreus* is present in the Arctic basins, abundances tend to be higher toward the basin fringes. Further, if we assume that development only depends on temperature, model simulations indicate that *C. hyperboreus* found in the basins is likely spawned locally, however, when we include potential food-limitation, it becomes unlikely that individuals spawned within the basins reach the first overwintering stage. Our results indicate that *C. hyperboreus* is resource-limited in the Arctic basins, and that individuals present in the basins are expatriates from the more productive shelf and slope areas.

Lique, Camille: Ifremer, camille.lique@ifremer.fr (Research Scientist)

Potential for deep convection in the Arctic Basin under a warming climate

Model studies have previously suggested a link between variations in the rate of deep water formation in the northern North Atlantic and variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC), but the dynamical link between the two is not fully understood. The goal of this study is to investigate the potential for deep Mixed Layer Depths (MLDs) to appear close to the sea ice edge in the Arctic Basin under a warming climate, and to quantify the potential contribution of deep convection in the Arctic Basin to the AMOC.

This study uses results from "present day" simulations of two climate models, CNRM and HiGEM, and also from simulations with a four times increase in atmospheric CO2 levels, representing a future, warmer climate. Under a warming climate, we expect (i) a reduction of the AMOC, (ii) a shoaling of the MLD in the North Atlantic and (iii) a northward retreat of the sea ice edge.

First, we document the changes affecting the MLD in the Arctic and the North Atlantic under a warming climate. There is a strong shoaling of the MLD in the present-day areas of deep convection in the North Atlantic, but also a deepening in the Eurasian Basin of the Arctic Ocean, where the MLD can episodically reach up to ~1000m. A detailed examination of the temporal and spatial structures of the changes affecting the ocean surface properties reveals that the Eurasian Basin undergoes a strong surface warming (linked with the retreat of the sea ice edge) and a strong salinization (possibly due the intensification of the surface gyres in the Arctic driven by stronger surface stress as the sea ice pack is thinning and shrinking). Together, these changes decrease the stratification, which triggers convective events in the basin.

Second, a quantitative Lagrangian diagnostic is applied to climate model output in order to determine where the mixed layer subduction contributes to the Atlantic Meridional Overturning Circulation at 26°N. We find that, for "present-day" conditions, the main contributions to the AMOC are mixed layer subduction in the Labrador, Irminger and Greenland Seas. In contrast, in the 4xCO2 simulations, the AMOC is greatly reduced and mixed layer subduction in the Arctic Basin and the subtropical gyre contribute significantly to the AMOC, the latter being likely related to a change of the stratification in this region.

Lowry, Kate: WHOI - USA, klowry@whoi.edu (Postdoc)

Under-ice phytoplankton bloom dynamics controlled by spring convective mixing in refreezing leads of open water

Spring phytoplankton growth in polar marine ecosystems is limited by light availability beneath ice-covered waters, particularly early in the season prior to snowmelt and pond formation. Leads of open water increase light transmission to the ice-covered ocean and are potentially important sites for enhanced primary production. Here we explore the role of leads in controlling the initiation of phytoplankton blooms within the sea ice zone of the Arctic Ocean. Data are presented from spring measurements in the Chukchi Sea during the Studies of Under-ice Blooms In the Chukchi Ecosystem (SUBICE) program in May-June 2014. Observations revealed that while fully consolidated sea ice occasionally supported modest under-ice blooms, sea ice with higher concentrations of leads had significantly lower phytoplankton biomass, despite high nutrient concentrations in surface waters. Through an analysis of hydrographic and biological properties, we attribute this counterintuitive finding to the occurrence of springtime convective mixing in refreezing leads of open water. Our results demonstrate that waters beneath loosely consolidated sea ice (e.g. 85-95% ice concentration) had weak stratification and were frequently mixed below the critical depth (the depth at which depth-integrated production balances depth-integrated respiration). These findings are supported by model calculations of under-ice light, primary production, and critical depth at varied lead fractions. The model demonstrates that under-ice blooms can form in stratified waters even beneath snow-covered sea ice but not in more deeply mixed waters beneath ice with refreezing leads. Future estimates of primary production must account for these phytoplankton dynamics in ice-covered waters.

Luneva, Maria: National Oceanography Centre - UK, mane1@noc.ac.uk (Research Scientist)

Evaluation of cross-shelf exchange in the Arctic Ocean on the multi-decadal scale.

The coupling between the continental shelves and the deep ocean is a key facet of the Earth System. Physical and biogeochemical constituents are controlled by markedly different processes in the two environments, where continental shelves are strongly impacted by: terrestrial inputs, tidal mixing, growth of coastal-trapped waves and rapid communication with the atmosphere. In the Arctic this issue is modulated by the unique physical oceanographic environment arising from the combination of sea ice, weak currents, weak interior stratification, strong and persistent surface stratification and broad continental shelves. Here we explore the processes mediating this exchange. We examine this with results from a 1/4o pan Arctic model (Luneva et al., 2015), based on an extraction of the NOC global ORCA025 model, but including features appropriate for shelf seas. We compare results of three 30-year long (1990-2010) simulations: with explicitly resolved tides and without any tidal dynamics; with climatology river runoff or inter-annual variability included. For the latter we use Dai et al., 2009 database combined with freshwater source from melting Greenland glaciers (Bamber et al., 2012). We evaluate shelf-deep ocean exchange fluxes across the isobaths 300m: Ekman surface and bottom drains, eddy-induced and tidally induced offshore-onshore mass and buoyancy fluxes. Preliminary analysis shows that the Benthic Ekman drain is persistent and continuous, but weak (0.3 SV). Cascades are dominant process of cross shelf exchange with totally 0.8-1.2Sv mass flux (~x3 Benthic Ekman), are highly localized, with the strongest cross-shelf volume exchange in the Laptev, Kara, Beaufort and Chukchi Seas. Wind provides only a weak transport (~x0.5 Benthic Ekman) in this area. Across slope velocities are about 1/10 the along slope currents. Cascading is negatively correlated with surface Ekman drain, driven by wind. We discuss inter annual variability of shelf-ocean exchange processes related with the variability of wind circulation and strong sea-ice summer retreat observed during the last decade. Using analysis of model output: sea ice velocities, subsurface, Ekman and geostrophic velocity of the ocean we analyze practical methods of determining of the wind-driven Ekman cross-shelf mass fluxes from observations.

Manucharyan, Georgy: California Institute of Technology, gmanuch@gmail.com, Postdoc

The influence of continental slopes on eddy and freshwater dynamics of the Beaufort Gyre

Understanding and accurately modeling mechanisms governing variations of the Beaufort Gyre freshwater reservoir remains challenging. Recent hypotheses were put forward suggesting that the freshwater and halocline dynamics is determined by a balance (or lack thereof) between the Ekman pumping from the anticyclonic winds and the counteracting mesoscale eddy transport. The eddies cumulatively act to iron out any gradients in isopycnal layer thickness — a critical process that is parameterized in low-resolution climate models using the Gent-McWilliams eddy diffusivity. According to idealized BG models and theory, the mean halocline depth and its equilibration time are inversely proportional to the eddy diffusivity — a parameter that itself depends on energetics and stability properties of the geostrophic currents and hence is a spatially inhomogeneous quantity.

Manucharyan, Georgy: California Institute of Technology, gmanuch@gmail.com, Postdoc

Submesoscale sea ice-ocean interactions in marginal ice zones.

G.E. Manucharyan and A.F. Thompson

Signatures of ocean eddies, fronts and filaments are commonly observed in marginal ice zones (MIZ) from satellite images of sea ice concentration, \textit{in situ} observations via ice-tethered profilers or under-ice gliders. Localized and intermittent sea ice heating and advection by ocean eddies are currently not accounted for in climate models and may contribute to their biases and errors in sea ice forecasts. Here, we explore mechanical sea ice interactions with underlying submesoscale ocean turbulence. We demonstrate that the release of potential energy stored in meltwater fronts can lead to energetic submesoscale motions along MIZs with sizes O(10 km) and Rossby numbers O(1). In low-wind conditions, cyclonic eddies and filaments efficiently trap the sea ice and advect it over warmer surface ocean waters where it can effectively melt. The horizontal eddy diffusivity of sea ice mass and heat across the MIZ can reach O(200 m^2/ s). Submesoscale ocean variability also induces large vertical velocities (order of 10 m/day) that can bring relatively warm subsurface waters into the mixed layer. The ocean--sea ice heat fluxes are localized over cyclonic eddies and filaments reaching about 100 W/m^2. We speculate that these submesoscale-driven intermittent fluxes of heat and sea ice can potentially contribute to the seasonal evolution of MIZs. With the continuing global warming and sea ice thickness reduction in the Arctic Ocean, submesoscale sea ice-ocean processes are expected to become increasingly prominent.

Marshall, John: MIT - USA, johncmarshall54@gmail.com (Professor)

Arctic Climate Response Functions

Authors: John Marshall, Jeffery Scott and Gianluca Meneghello

We review progress on Arctic Climate Response Functions, a modeling project which explores how the Arctic responds to changes in external forcing. Our goal is to compute and compare “Climate Response Functions” (CRFs) --- the transient response of key observable indicators such as sea-ice extent, freshwater content of the Beaufort Gyre, etc. --- to abrupt “step” changes in forcing fields across a number of arctic models. Changes in wind, freshwater sources and inflows to the Arctic basins are considered.

A first FAMOS group paper entitled ‘Freshwater response of the Beaufort Gyre to a step change in the Beaufort High: model comparisons.’ is in preparation. Key topics which have emerged are (i) the role of sea-ice in mediating the transfer of stress to the ocean and how this is represented in models (ii) the parameterization of mesoscale eddy fluxes.

Finally, other emerging projects within the Arctic CRF theme will be discussed.

See the FAMOS website for a detailed view of the project:
http://famosarctic.com/members/people/teams/13

Maslowski, Wieslaw: Naval Postgraduate School, maslowsk@nps.edu, Professor

Sensitivity of Arctic Sea Ice and Climate States to the Oceanic Exchanges Across the Main Arctic Gateways

Authors: W. Maslowski, R. Osinski, Y. Lee

Realistic modeling of the oceanic mass and property exchanges across the main Arctic gateway is critical to representing their impact on sea ice variability and climate change at seasonal to interannual and decadal time scales. However, ocean models commonly struggle with representing transports through the narrow and shallow gates, controlling Arctic-sub- Arctic fluxes. Yet, oceanic fluxes associated with the northward advection of Atlantic or Pacific water, are critical to understanding, simulation and prediction of their impact on the sea ice cover and related feedbacksto the atmosphere and climate.

To address some of these challenges, we present updated results from several simulations of the Regional Arctic System Model (RASM), focusing on oceanic fluxes across the Arctic gateways. RASM is a pan-Arctic, coupled atmosphere - ice - ocean - land model. Four ocean and sea ice model configurations are used: 1/12º (~9.3km) or 1/48º (~2.4km) with 45 or 60 vertical layers configured on rotated sphere meshes.

The main objective of this presentation is to quantify the oceanic fluxes in and out from the Arctic Ocean and to understand their sensitivity to model spatial configurations and varying parameter space as well as their impacts on sea ice and climate.

Martin, Torge**:** GEOMAR Helmholtz Centre for Ocean Research Kiel,
torge.martin@gmail.com

Enhanced Greenland melting: Effect of mesoscale ocean dynamics on distribution, timing and impact

Enhanced melting of the Greenland ice sheet under global warming is expected to have an impact on the formation of deep water in the subpolar North Atlantic with possible consequences for the Atlantic meridional overturning circulation. In a series of experiments with a global 0.5˚ setup of the ocean/sea-ice model NEMO/LIM we study the role of mesoscale eddies in distributing the meltwater and influencing timing and intensity of its impact. The role of eddies is addressed by repeating experiments with a similar setup applying a 0.1˚ nest to the North Atlantic region between 30˚N and 80˚N. Enhanced Greenland runoff is prescribed as a spatially varying climatology derived from the data of Bamber et al. (2012, GRL), which is scaled to match an annual total of 0.05 Sv and 0.1 Sv respectively. Runoff is either enhanced instantaneously or ramped up following the observed trend.

Meneghello, Gianluca: MIT, mgl@mit.edu, PostDoc

Observations of seasonal upwelling and downwelling in the Beaufort Sea mediated by sea ice

We present and discuss updated observational and numerical estimates of Ekman pumping over the Beaufort Sea. We differ from previous studies by including the effect of surface geostrophic currents into our computations.

Miller, James: Rutgers University - USA, miller@marine.rutgers.edu (Professor)

A Lagrangian Analysis of Arctic Freshwater Pathways

Marie McCrary and James Miller

A dominant physical characteristic of the Arctic Ocean is the presence of large volumes of freshwater, primarily owing to the inflow of low salinity Pacific water through the Bering Strait, North American and Eurasian river runoff, and atmospheric precipitation. Sea ice melt within the Arctic provides an additional local source of freshwater. One major reservoir of freshwater is the Beaufort Gyre that is estimated to hold about ten times more freshwater than the annual freshwater flux into the basin. Any changes in the freshwater content of the Beaufort Gyre 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. The sparse network of observations in the Arctic Ocean leads to substantial uncertainty in the long-term variability of the liquid freshwater pathways in the Arctic. We resolve some of this uncertainty by investigating the variability of Arctic Ocean freshwater sources, storage, and export between 1993 and 2013 using Lagrangian passive tracers with the Global Ocean Physics Reanalysis (GLORYS) that is based on the Nucleus for European Modeling of the Ocean (NEMO) model. 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.

Myers, Paul: University of Alberta, pmyers@ualberta.ca

Modelling Greenland icebergs: pathways and freshwater contribution

Juliana M. Marson, Paul G. Myers, and Xianmin Hu

Since icebergs are an important freshwater source to the ocean and a threat to navigation, understanding the distribution of Greenland icebergs has become essential. These paths, however, are scarcely documented and observations using remote sensing is limited by sea ice cover and the size of icebergs. Our study aims to evaluate the trajectories of icebergs that calve from Greenland – and their potential contribution to the Labrador Sea as a source of freshwater – using the Nucleus for European Modelling of the Ocean (NEMO v3.4) coupled with two versions of an iceberg module. The baseline version, used in all previous studies concerning Greenland icebergs, uses only the surface state of the ocean produced by the ocean model to move and melt icebergs. The second version, an improvement only applied to the Southern Ocean until now, allow the icebergs to interact with the three-dimensional ocean fields. When comparing the icebergs' distribution obtained by two simulations – each one using one version of the iceberg module, but otherwise identical – we observed that icebergs tend to move offshore when vertically-integrated ocean fields are taken into consideration. By dividing the Greenland coast into five sectors of origin, we also found out that while Baffin Bay is preferentially occupied by icebergs calved from western Greenland, most icebergs that reach the interior of Labrador Sea calved from the southeast sector. If, therefore, calving rates were to accelerate along the southeastern Greenland coast, our results suggest that this could have important implications for the deep convection known to occur in the Labrador Sea.

Muilwijk, Morven: University of Bergen, Geophysical Institute, morven@uib.no, PhD student

Atlantic Water and sea ice variability in the 20th century Arctic Ocean from a global ocean model and observations

Both historical observations and outcome from a fully coupled earth system model show a warming trend in core temperature of Atlantic Water entering the Arctic Ocean over the last few decades (1977-2015). A portion of this recent warming has been attributed to the current global warming and possibly anthropogenic activity. However, past periods of warm Atlantic Water (1930-1940) have been documented. We believe that the Atlantic Water warming trend in the Arctic Ocean may be part of long-term multidecadal variability, which is influenced and reinforced by strong anthropogenic forcing.

We have therefore investigated the interannual, decadal and multidecadal variability of Atlantic Water and sea ice in the Arctic Ocean using a global ocean model. Here we present results from a simulation for the period 1871-2009 with the ocean-sea ice component of the Norwegian Earth System Model (NorESM-O) forced by a Twentieth Century Reanalysis data set, which are compared with available hydrographic measurements of Atlantic Water in the Fram Strait and north of Svalbard, and observations of sea ice.

The simulation shows several periods of relatively warm Atlantic Water before the 1970s. Also, there appears to be a correlation with Atlantic Water heat and Arctic sea ice volume. We find, for example, that the 1930s warm period was followed by a loss of Arctic sea ice volume.

In addition, passive tracers were released in the model simulation to explore the circulation pattern of Atlantic Water, the variability of recirculation of Atlantic Water in the Fram Strait and distribution of freshwater from different river sources. These tracers show that most Atlantic Water either circulates in the Nansen Basin or recirculates back to the Fram Strait relatively quickly, and that only a very small portion crosses over to the Canadian side of the Lomonosov Ridge. They also reveal some of the different sources of the freshwater content of the Beaufort Gyre.

Murashkin, Dmitrii: University of Bremen, Germany - murashkin@uni-bremen.de (PhD Student)

Lead distribution in the European Arctic derived from Sentinel-1 SAR images

The presence of leads with open water or thin ice is an important feature of the Arctic sea ice cover. Leads regulate the heat, gas, and moisture fluxes between the ocean and the atmosphere and are places of increased sea ice production during winter time. Life of Arctic animals and organisms is often attached to leads. An algorithm providing an automatic lead detection based on Synthetic Aperture Radar (SAR) images is developed and applied for three winter seasons in the European Arctic.

The Sentinel-1 constellation of two satellites providing dual-channel C-band measurements (co- and cross-polarized modes) independent of weather and season is used. Leads are identified in single scenes and then combined to maps covering a larger region. 2-daily composite lead maps of the European Arctic show higher occurrence of arc-shaped leads north of the Fram Strait. A time series of lead maps is obtained for three consecutive winter seasons (2014–2017). Lead concentrations are derived from these maps and compared with results of algorithms utilizing MODIS and CryoSat-2/SIRAL observations. Size distribution and lead occurrence probability are analyzed.

Nguyen, An: University of Texas at Austin, antnguyen13@gmail.com, Senior research scientist

Investigation of Arctic Ocean mixing in an ocean-sea ice state estimation framework

Investigation of inverted 3D mixing fields in the Arctic Subpolar gyre sTate Estimate using ITP and other hydrographic observations as constraints.

Oikkonen, Annu: Finish Meteorological Institute, annu.oikkonen@fmi.fi, Researcher

Small-scale sea ice deformation during N-ICE2015: From compact pack ice to marginal ice zone

We studied sea ice deformation from ship radar images recorded during the N-ICE2015 campaign. The campaign consisted of four consecutive drifting ice stations north of Svalbard, with a total duration of nearly 5 months. With the ship radar images the study on sea ice deformation could be extended to smaller scales than previously possible: the length scales ranging from 50 m to few kilometers and the time scales ranging from 10 min to 24 h. The deformation rates were found to follow power law scaling with respect to length and time scale even on this small scale and in small domain (15 km × 15 km). The length scale dependence of deformation rate depends on the time scale: the power law scaling exponent β of the whole study period decreases from 0.82 to 0.52 with the time interval increasing from 10 min to 24 h. The results emphasize the local and intermittent nature of the sea ice deformation. The obtained length and time scale dependences enable the comparison of the deformation rates recorded in different length and time scales (for instance deformation rates from the satellite based RGPS and the drifting buoys).

Data collected during the N-ICE campaign represents a wide variety of conditions from the compact pack ice to marginal ice zone (MIZ). Deep in the ice pack, high deformation rates occurred only with high wind and drift speed, while in MIZ they were found also during calm conditions. Also, the length scale dependence of sea ice deformation rate was found to be stronger (greater magnitude of β) when going closer to the ice edge.

Ono, Jun: Japan Agency for Marine-Earth and Technology, Japan - jun.ono@jamstec.go.jp (Researcher)

Mechanisms influencing seasonal-to-interannual prediction skill of sea ice extent in the Arctic Ocean in MIROC

To assess the skill of predictions of the seasonal-to-interannual detrended sea ice extent in the Arctic Ocean (SIE) and to clarify the underlying physical processes, we conducted ensemble hindcasts, started on January 1st, April 1st, July 1st, and October 1st for each year from 1980 to 2011, for lead times of up three years, using the Model for Interdisciplinary Research on Climate (MIROC) version 5 initialized with the observed atmosphere and ocean anomalies and sea ice concentration. Significant skill is found for the winter months: the December SIE can be predicted up to 1 year ahead. This skill is attributed to the subsurface ocean heat content originating in the North Atlantic. The subsurface water flows into the Barents Sea from spring to fall and emerges at the surface in winter by vertical mixing, and eventually affects the sea ice variability there. Meanwhile, the September SIE predictions are skillful for lead times of up to 3 months, due to the persistence of sea ice in the Beaufort, Chukchi, and East Siberian Seas initialized in July, as suggested by previous studies.

Panteleev, Gleb: Naval Research Laboratory - USA, gleb.panteleev@nrlssc.navy.mil

Anomalous circulation in the Pacific sector of the Arctic Ocean in July-December 2008

Gleb G. Panteleev, Oceana P. Francis , Max Yaremchuk, Jinlun Zhang, Mikhail Kulakov

Variability of the mean summer-fall ocean state in the Pacific Sector of the Arctic Ocean (PSAO) is studied using a dynamically constrained synthesis (4Dvar) of historical *in situ* observations collected between 1972 and 2008. Specifically, the oceanic response to the cyclonic (1989-1996) and anticyclonic (1972-1978, 1997-2006) phases of the Arctic Ocean Oscillation (AOO) is assessed for the purpose of quantitatively comparing the 2008 circulation pattern that followed the 2007 ice cover minimum.

It is shown that the PSAO circulation during July-December of 2008 was characterized by a pronounced negative Sea Surface Height (SSH) anomaly along the Eurasian shelf break, which corresponds a significant decline of the transport in the Atlantic Water (AW) inflow region into the PSAO and increased the sea level difference between the Bering and Chukchi Seas. This anomaly agrees well with the observed amplification of the Bering Strait transport carrying fresh Pacific Waters into the PSAO. Largrangian analysis of the optimized solution suggests that the freshwater (FW) accumulation in the Beaufort Gyre has a negligible contribution from the East Siberian Sea and is likely caused by the enhanced FW export from the region north of the Canadian Archipelago/Greenland.

The inverse modeling results are confirmed by validation against independent altimetry observations and *in situ* velocity data from NABOS moorings. It is also shown that presented results are in significantly better agreement with the data than the output of the PIOMAS model run utilized as a first guess solution for the 4dVar analysis.

Panteleev G., M. Yaremchuk, T. Townsend, D. Herbert, R. Allard

Naval Research Laboratory, Stennis Space Center

Impact of ice thickness assimilation into the CICE model on the short-term ice forecast.

Ice thickness (IT) data is an important source of information on ice dynamics complementing ice concentration (IC) under the winter conditions when the amount of information provided by the IC field deteriorates, causing quick loss in the forecast skill of the data-driven model solutions. We present preliminary results of assimilating 2-day averaged IT data from the Sentinel-1a satellite into the CICE v5.12 ice model using the diffusion-based cross-correlations incorporating ice velocities from the background solution. Impact of various formulations of the IT/IC cross correlation model on the forecast skill will be presented and discussed.

Panteleev et al.: **Observing System Simulation Experiments and Adjoint Sensitivity Analysis - efficient methods for optimization and planning of the observational programs in the Arctic Ocean**

Over recent decades, the Arctic Ocean (AO) has experienced profound climate changes. To study these climate changes, several regional observational programs have been started. Due to complicated logistics and remoteness, in situ observations in the AO are extremely expensive.Therefore, an Efficient Ocean Observational System in the Arctic Ocean is critical toward understanding environmental changes in the Arctic. Observing System Simulation Experiments (OSSE) and Adjoint Sensitivity Analysis (ASA) are powerful tools that could be used in the optimization of existing and incoming observational programs in the AO. These optimal planning tools recommended by the SEARCH implementation plan and widely used in atmospheric research, are still rarely implemented in physical and biological oceanography. We provide several examples of how the OSSE and ASA can be used to optimize the locations of High Frequency Radars, biological tracer surveys, and toward creating an inexpensive drifter observational program capable of providing sufficient information in the reconstruction of the circulation in the northern Bering, Chukchi and southern Beaufort Seas.

Pemberton, Per: SMHI, per.pemberton@smhi.se, Researcher, Sweden

Arctic Ocean (steady state) response to freshwater and wind perturbations

Here we investigate how the Arctic Ocean responds, in a steady state sense, to changes in freshwater input and wind stress anomalies in a series of experiments using a state-of-the-art coupled ice-ocean-circulation model (MITgcm). The simulations yield marked changes in the cold halocline and the Arctic Atlantic layer.

A simple conceptual model of the Arctic Ocean, based on a geostrophically controlled discharge of the low-salinity water, is introduced and compared with the simulations. Key predictions of the conceptual model are that the halocline depth should decrease with increasing freshwater input and that the Arctic Ocean freshwater storage should increase proportionally to the square root of the freshwater input, which are in broad qualitative agreement with the sensitivity experiments. However, the model-simulated rate of increase of the freshwater storage is weaker. The response due to wind stress changes are strong and comparable to +/- 50% in runoff and precipitation.

Proshutinsky, Andrey: WHOI, aproshutinsky@whoi.edu, Senior Scientist

Beaufort Gyre freshwater content changes in 2003-2016

Proshutinsky and 9 co-authors

The 2003-2016 hydrographic data collected from research cruises, moorings, Ice-Tethered buoy observations and satellite altimetry for the Beaufort Gyre region of the Arctic Ocean document an increase of over 6500km^3 of liquid freshwater content (FWC) (a 40% growth) relative to climatology of the 1970s. This freshwater (FW) accumulation was a result of persistent anticyclonic atmospheric forcing (1997-2016) accompanied by sea ice melt, an anomalous wind-forced redirection of Makenzie River discharge from predominantly eastward to westward flow supplying the Beaufort Gyre region with its FW and freshwater supply coming with waters of Pacific Ocean origin via Bering Strait. A slight decrease of FWC in the region between 2010 and 2013 was associated with a weak relaxation in wind forcing; however, in 2015 and 2016, the magnitude of FWC in the region was greater than ever measured previously due to combination of intensification of anticyclonic winds and FW supply from both ice melt and river discharge. In general, numerical models reproduce tendency of FW accumulation in the Beaufort Gyre region very well but underestimate FWC changes due to unavoidable numerical mixing.

Proshutinsky, Andrey: WHOI, aproshutinsky@whoi.edu, Senior Scientist

Sea level changes in the Arctic Ocean (1954-2016)

Proshutinsky A., R. Krishfield and I. Ashik

Sea level (SL) time series from coastal stations in the Siberian Seas (Kara, Laptev, East Siberian and Chukchi) for the period of 1954--2016 are analyzed to investigate the major features of Arctic sea level variability at decadal time scales. The estimated rate of SL rise for these stations over the 1954 --2016 is 2.82 ± 0.35 mm per year (after correction for glacial isostatic adjustment, GIA). Until the late 1990s, the SL time series correlate relatively well with the AO index and with the inverse of the sea level atmospheric pressure (SLP) at the North Pole, but then due to sea ice melt, warming of surface layers and persistent anticyclonic winds, the sea level regime changed. Consistent with these influences, sea level dropped significantly after 1990 and reached a minimum in 1996--1997 when the circulation regime changed from cyclonic to anticyclonic. In contrast, from 1997 to 2006 the mean SL has generally increased while the AO and SLP remained more or less stable. After 2008, sea level has had a decreasing tendency, showing no apparent correlation with the AO nor SLP at the North Pole. Since sea level change exhibits large interannual variability and is the net result of many individual effects of environmental forcing, it is difficult to evaluate the significance of the change in relative terms. Although not statistically robust, the changing tendency toward decreasing SL rise may be due to steric effects associated with some stabilization of surface ocean warming and its freshwater content.

Questel, Jennifer: University of Connecticut - USA, jennifer.questel@uconn.edu (Postdoc)

Pan-Arctic phylogeography and connectivity of species of Pseudocalanus (Copepoda, Calanoida)

Phylogeographic analysis of marine zooplankton species can reveal patterns of population connectivity. Three species of the copepod genus Pseudocalanus exhibit widespread distributions over polar and sub-polar latitudes of the northern hemisphere. These species are frequently highly abundant and may be ecologically important as links to higher trophic levels. We report findings based on phylogeographic analysis of the mitochondrial cytochrome oxidase I (COI) gene for Pseudocalanus acuspes, P. minutus and P. newmani from Atlantic and Pacific sectors of the Arctic Ocean. Population connectivity was evaluated using Migrate-N to estimate the magnitude of directional, asymmetrical, non-equilibrium migration rates and evaluate hypothesized migration models based on Bayesian statistics. Pan-Arctic dispersal patterns and pathways were shown to differ among the three species of Pseudocalanus: for P. acuspes the N. Atlantic Current and Pacific currents are most important; P. minutus shows Pan-Arctic connectivity; and P. newmani shows panmixis among the sampled locations. Pan-Arctic phylogeographic analysis of widely-distributed and ecologically-important species can provide new insights into how a warming Arctic with diminishing sea-ice cover may reduce barriers to gene flow and alter patterns of population connectivity for Arctic and sub-Arctic copepods and other marine zooplankton species.

Richter, Maren: Alfred Wegener Institute Bremerhaven, mrichter@awi.de

Fram Strait recirculation and the EGC north of 79°N, synoptic observations and model comparison

Fram Strait, located between Greenland and Svalbard, is a gateway for heat and nutrient transport to the Arctic Ocean and sea-ice export from the Arctic. Large outlet glaciers of the Greenland ice-sheet interact with the regional ocean circulation with ramifications for mass loss to the ocean. Relatively warm Atlantic Water (AW) is transported northward in the eastern Fram Strait via the West Spitsbergen Current (WSC); in the western Fram Strait the East Greenland Current (EGC) transports colder, fresher water of Arctic origin southward. Part of the AW in eastern Fram Strait is not transported to the Arctic Ocean, but instead flows westward to join the EGC (it recirculates). Although crucial for understanding AW pathways to large outlet glaciers through two troughs (Westwind Trough and Norske Trough) on the East Greenland shelf, it is not known at what latitudes AW joins the EGC and how that changes the structure of the EGC. Here we present synoptic hydrographic and velocity data collected by RV Polarstern in summer 2016 that contribute to answering these questions. Four sections cross the EGC between 77.8° N and 80.8° N; two are located at the mouths of the troughs, one crosses the EGC, central Fram Strait and the WSC. A meridional section at 0° EW spans the recirculation in the central Fram Strait. These data allow the first estimate of absolute geostrophic transports of different water masses (e.g. AW and Denmark Strait Overflow Water), their propagation and transformation in the recirculation and the EGC north of 79° N at an appropriate spatial resolution. Below Polar Surface Water, AW and colder Arctic Atlantic Water are located horizontally next to each other and then intermittently mix as they flow southward in the EGC. No AW is found directly in front of Westwind Trough, though it is found inside Norske Trough further to the south. The northward extent of the recirculation in the synoptic sections in Fram Strait is 80.8° N, however, further investigations are needed to test whether this is representative. The velocity field along 79° N is highly variable (and markedly different from time-mean realizations) with evidence of surface intensified eddies traveling westward. The observations of the EGC south of 79.6° N display a typical boundary current structure. Conversely, at 80.2° N the isopycnals near the shelfbreak are only weakly sloped. Analysis of sections from an eddy resolving numerical model of Fram Strait corroborate our findings.

Shibley, Nicole: Yale University - USA, nicole.shibley@yale.edu (Graduate Student)

Double-Diffusive Layer Formation in the Presence of Turbulence in the 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. Several past studies have examined mechanisms that govern the observed thicknesses of staircase mixed 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 theory to consider the influence of turbulence on mixed-layer thicknesses. We find that increased diffusivity ratios (ratios of salinity diffusivity to thermal diffusivity) result in thicker steps that take longer times to form. The temperatures of these mixed layers are larger than their counterparts of smaller diffusivity ratio. Layer mergers take place more frequently and more rapidly for smaller values of diffusivity ratio. The study has implications for the Arctic Ocean where double-diffusive staircases are widely present, and mixed-layer thicknesses are well-resolved by ocean measurements. Our theoretical framework provides a means to determine turbulent diffusivities (in regions where microstructure measurements are not available) by considering only observations of density ratio, stratification, and layer thicknesses.

Schourup-Kristensen, Vibe: Alfred-Wegener-Institute, Germany, vschourup-kristensen@awi-polarstern.de, PhD Student

Effect of horizontal resolution on modeled sea ice algae

Sea ice algae is thought to play an important role in the Arctic ecosystem. The strong physical-biogeochemical coupling in the Arctic means that the representation of sea ice algae in large scale ocean general circulation ice algae models is strongly dependent on the representation of ice and ocean physics. One way of improving the physics is by increasing the horizontal resolution.

Here, we present results of the Sea Ice Model for Bottom Algae (SIMBA) coupled to the Finite Element Sea-ice Ocean Model (FESOM). We utilize FESOM's unstructured mesh capability to perform two runs with a 20 (reference) and 4.5 (high) km horizontal resolution, respectively. The higher resolution acts to introduce a larger heterogeneity in the sea ice regarding thickness and thus transmittance of light. Sea ice algae, which is located at the bottom of the ice, can thus develop independently around leads in the high resolution run, while it spreads northwards more homogeneously in the reference run. As a consequence, the average chlorophyll a concentration is higher early in the season in the 4.5 km run, while this run has a stronger nitrate limitation towards the end of the season. A next step will be to couple the FESOM-SIMBA to an oceanic biogeochemical model, thereby improving feedback mechanisms with the ocean.

Schultz, Cristina: WHOI/MIT, cschultz@whoi.edu, PhD student

A new regional model for the study of the carbon cycle and ocean acidification in the Gulf of Alaska

There are few observations related to carbonate cycle and CaCO3 underaturation in the coastal waters of the Gulf of Alaska. However, the observations that exist suggest seasonal subsurface aragonite undersaturation, which could have detrimental consequences to CO2 sensitive species, altering the food web structures and potentially leading to ecosystem and socio-economic consequences. Enhanced glacial melting lead by climate change could accelerate the progression of ocean acidification in the Gulf of Alaska even further. However, the currently limited spatial and temporal data coverage precludes a detailed conceptual understanding of the physical and biological mechanisms controlling the local carbon dynamics and thus impedes our ability to anticipate and mitigate future changes. In this context, ocean modeling is a powerful tool to fill the gaps left by sparse data and test the influence of increased fresh water runoff in the carbon cycle. We will show some first results from our moderately high resolution, carbon based biogeochemical regional model (ROMS-Cobalt, 4.5 km) that is forced explicitly with coastal freshwater discharges, to better represent the ongoing climate change driven melting of glaciers. The model results, compared against climatology data sets, moorings and cruise data, will give insights into seasonal and interannual variability of enhancing and inhibiting controls of ocean acidification and to detangle the complex interplay of mechanisms that drive aragonite undersaturation.

Schweiger, Axel: Polar Science Center/Applied Physics Laboratory/University of Washington, axel@apl.uw.edu, Senior Principal Scientist

The Sea Ice Drift Forecast Experiment

Axel Schweiger[1], *Helge Goessling*[2], *Ed Blanchard-Wrigglesworth*[3], *Thomas Krumpen*[2], *Marcel Nicolaus*[2], Ignatius Rigor[1,], Bob Grumbine[4]

[1]*Polar Science Center, Applied Physics Laboratory, University of Washington*
[2]*Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research*
[3]*Department of Atmospheric Sciences, University of Washington*
[3]*Department of Atmospheric Sciences, University of Washington*
[4]NOAA-NCEP/EMC Marine Modeling and Analysis Branch

The Sea Ice Drift Forecast Experiment SIDFEx was launched during summer of 2017. SIDFEx is a community effort to solicit, collect, and analyze sea ice drift forecasts, based on arbitrary methods, for a number of sea-ice buoys on a regular basis.

The initiative is inspired by increasing research and operational needs to forecast future positions of assets (e.g. buoys, ships) drifting in Arctic sea ice. An example is the need to determine an optimal deployment position of the research icebreaker *Polarstern* when she will start her year-long drift across the Arctic in autumn 2019 (MOSAiC drift). Specifically, it is unclear whether forecast systems that account for initial conditions and provide forecasts of the evolving atmosphere, ice, and ocean system, can provide additional skill over drift forecasts made using historical sea ice velocity fields. The MOSAiC drift provides a template for assessing the capabilities to forecast sea-ice drift for a range of applications, ranging from logistics support for future field experiments to potential search and rescue operations. The examination of sea ice drift forecasts provides an integrated assessment of many aspects of the coupled atmosphere-ice-ocean system and will motivate in depth investigations into how key variables are measured, modeled, and forecast. In particular we expect coordinated drift forecasts to draw attention to the interaction between sea ice physics and boundary layer physics in both atmosphere and ocean. We expect that a systematic assessment of real drift forecasting capabilities will improve our physical understanding of sea ice and enable us to identify and resolve model shortcomings and identify limits of predictability.

We will present the current design of SIDFEx and discuss initial results from 2017 submissions.

Schweiger, Axel: Polar Science Center/Applied Physics Laboratory/University of Washington, axel@apl.uw.edu, Senior Principal Scientist

Spatiotemporal variability of Arctic sea ice thickness over the 20th Century

Axel J. Schweiger, Jinlun Zhang, Kevin Wood

The state of our knowledge about sea ice variability before 1979 is limited to information about sea ice extent and concentration assembled from shipping logs and very little is known about the variability of sea ice thickness and total sea ice volume. To expand our understanding of sea ice variability to a century scale record, we use the Panarctic Ice and Ocean Modelling and Assimilation system (PIOMAS) to generate a sea ice reanalysis from 1900 to 2010 (PIOMAS-20C). PIOMAS-20C is generated by forcing PIOMAS with atmospheric reanalysis data from the ERA-20C project. We present results that include validation of atmospheric forcing parameters over sea ice from the ERA20C project. Sea ice information extracted from recently digitized shipping logs from the early part of the 20Th century will be compared to PIOMAS-20C. PIOMAS-20C sea ice thickness is generally in good agreement with available observations before and after 1979. We investigate patterns of sea ice thickness and volume variability in the early 20th century and contrast them with sea ice changes over the past 35 years.

Scott, Jeffery: MIT, jscott@mit.edu, Research Scientist

Climate Response Functions for the Arctic

TBD

Smedsrud, Lars H.: University of Bergen, larsh@gfi.uib.no, Professor

Simulating variability in the Fram Strait sea ice export and related Arctic sea ice response

The long-term annual Fram Strait sea ice area export is about 880 000 km², representing about 10% of the sea-ice-covered area inside the Arctic basin. This export has large inter-annual and multi-decadal variability, but apparently no long-term trend. However, during the last decades, the amount of ice exported has increased, with several years having annual ice exports that exceeded 1 million km². This large recent export has likely played an important role in the recent Arctic sea ice loss, explaining some of the observed summer ice loss and some of the general thinning (ice volume loss) occurring throughout the year.

Generally simulations only capture parts of the recent sea ice loss, and the role of natural variability in the ice loss remains a somewhat controversial issue. Because changes in the larger scale wind forcing is the primary cause of the ice export variability one would expect that regional and global ice-ocean models forced by observed (re-analysis) winds should re-produce the variability quite well. The global coupled air-ice-ocean models (CMIP5 type) have well documented correlations between large export anomalies and thinning, but generally export too much sea ice area.

This work will evaluate the simulated Fram Strait sea ice area export in the range of models used for the coordinated Climate Response Functions (CRF) set-up. Our initial focus is on the Greenland Sea wind forcing perturbations (GS-/GS+). Initial evaluation of the Norwegian Earth System Model (NorESM) shows that there is a large simulated variability correlating well with observations for 1935 - 2015. However, the mean export is about 10% larger than observations, which may explain a low bias in sea ice area. Our hypothesis is that increased ice export during winter will result in new ice growth and contribute to thinning inside the Arctic Basin, while increased summer or spring export will contribute directly the following September minima. Preliminary analysis suggest that the GS- perturbations decreases ice export significantly, while there is little change in export with GS+. GS- consequently produces a larger Arctic sea ice volume and a larger ice covered area, with largest response in the Atlantic sector during winter.

Spall, Michael: WHOI, mspall@whoi.edu

Ventilation of the halocline in the Canada Basin

A regional numerical model, mooring, and hydrographic data are used to identify the source and ventilation pathway of upper halocline waters in the Canada Basin. Absolute velocity measurements reveal a substantial westward flow just offshore of the Chukchi shelfbreak, the Chukchi Slope Current, that is present year-round and is composed largely of water masses that originated from the Chukchi Sea. The regional model produces a similar flow, and connects it to outflow at Barrow Canyon. Seasonal stratification and inertial effects are important factors in driving this flow across the isobaths. These results suggest that nonlinear advection downstream of Barrow Canyon represents the dominant ventilation mechanism for the western Arctic.

Steele, Mike: University of Washington, mas@apl.washington.edu, Senior Oceanographer

Upper Ocean Temperature in the Seasonal Ice Zone: UpTempO buoys

UpTempO drifting buoys ("Upper Temperature of the polar Oceans") provide hourly temperature data over the upper 60 meters (basins) or 25 meters (shelves) of the Arctic Seas. Thermistors are positioned on the floating hull at ~ 20 cm depth and along a sensor string at 2.5 m - 10 m intervals (lengthening with depth). They are designed to provide information on the summer warming and fall cooling of the upper ocean, where shortwave radiation and surface currents combine to warm the surface mixed layer and Near-Surface Temperature Maximum. A summary of the program and future developments will be provided. Google "uptempo arctic" to find out more.

Supekar, Rohit: MIT, srohit@mit.edu, Graduate student

Observations of Regional Inhomogeneity of Double-Diffusive Layering in the Arctic Ocean

Several observational studies have demonstrated the presence of double-diffusive staircases in the Beaufort sea of the Arctic ocean that are characterized by well-mixed layers sandwiched between high-gradient interfaces. Such structures are a result of double-diffusive convection, which occurs when cooler fresh water lies atop the warmer saltier Atlantic water layer.

To investigate the presence of double-diffusive layers, we analyze 10 days of moored data from the southeastern Canada basin. The data indicates a sudden appearance of layers between 300-400 m at the mooring location after about 6 days of deployment. A Shallow Water Integrated Mapping System (SWIMS) survey of the area illustrates that the sudden appearance of layers arises as a patch with no layering advects away from the mooring site. Preliminary analyses suggest that the lack of layers at these depths is associated with an eddy, which has discernibly different T-S properties. Such regional inhomogeneity of layers in ice-free regions is surprising as it contrasts with previous observations made using Ice-Tethered Profilers that have indicated coherence of layers over basin-wide spatial scales (Timmermans et al., 2008, Journal of Geophysical Research).

Terhaar, Jens: LSCE-IPSL, jens.terhaar@lsce.ipsl.fr, PhD student

Anthropogenic carbon in the Arctic Ocean

As well as climate change, the Arctic Ocean is projected to experience amplified ocean acidification, more than other oceans. To model its future changes, we must first be able to simulate the Arctic's baseline conditions and acidification over the industrial era. Although global ocean models are needed to assess centennial scale changes of ocean carbon, typical coarse-resolution models used to study ocean biogeochemistry may be inadequate to properly resolve the Arctic Ocean. Here we assess how simulations of ocean uptake of anthropogenic CO2 (the main driver of acidification) in a global ocean circulation-biogeochemistry model (NEMO-PISCES) change when moving from coarse to eddy permitting resolution. Although the Arctic Ocean contains only 1% of the global ocean volume, it stores about 2% of the global ocean's anthropogenic carbon. The Arctic's regional inventory is enhanced because about three-fourths of the anthropogenic carbon enters the Arctic Ocean through lateral transport rather than by a flux across the air-sea interface. The relative importance of lateral transport in the Arctic is more prominent than in other ocean regions except perhaps for the subtropical gyres. Net lateral transport of anthropogenic carbon into the Arctic Ocean increases with model resolution, enhancing the basin wide inventory. While the coarse-resolution model configuration ORCA2 (2°) stored 1.6 Pg C between 1860 and 2005, the eddying versions ORCA05 and ORCA025 (1/2° and 1/4°) retain 1.9 and 2.3 Pg C, respectively. Data-based estimates of anthropogenic carbon based on CFC-12 observations are higher (3.0 Pg C) but should be corrected downward by 10% based on tests of the data-based method in the ORCA025 model world. A 3-D model with eddying resolution appears necessary to properly simulate anthropogenic carbon in the Arctic Ocean. Our simulations and data-based assessment reduce the uncertainties on the quantity of anthropogenic carbon stored in the Arctic Ocean while providing insight into the physical mechanisms that control its enhanced storage.

Timmermans, Mary-Louise: Yale University, mary-louise.timmermans@yale.edu, Professor

Causes and implications of a warming Canada Basin halocline

Arctic Ocean measurements reveal sustained increases in ocean heat content in the Canada Basin halocline over at least the past decade. Since 2004, total heat content in the permanent warm halocline has increased by about 32%. This magnitude of heat increase per unit area would be sufficient to melt around 1-m of sea ice. We show how the halocline warming is linked to water-mass changes at the southwest margin of the basin, in the northern Chukchi Sea; observations indicate this region to be the major origin site for surface water masses to ventilate the interior halocline. This region has seen a more than 40% increase in summer solar absorption to the surface ocean since 2004, commensurate with reduced summer average sea-ice area. We show how the subsequent excess ocean heat content, combined with observational estimates of ventilation rates of surface-water masses in this region, is more than sufficient to account for the observed halocline warming in the interior. Future scenarios and implications to halocline structure and sea-ice cover are considered.

Townsend, Tamara Townsend: Naval Research Laboratory, tammy.townsend@nrlssc.navy.mil, Meteorologist

Preliminary Investigation of the Impact of Real-time In Situ Data Assimilation in the Navy's Arctic Prediction System

The U.S. Navy's Arctic prediction capabilities utilize a coupled ice-ocean modeling system consisting of the Community Ice CodE (CICE) and the HYbrid Coordinate Ocean Model (HYCOM) with atmospheric forcing from the Navy Global Environmental Model (NAVGEM). The Arctic Cap Nowcast/Forecast System (ACNFS) has been running operationally at the Naval Oceanographic Office since 2013 to provide 7-day forecasts of ice thickness, concentration, drift, and lead opening rates to the National Ice Center. Navy Arctic forecasting is being transitioned from ACNFS to the Global Ocean Forecast System version 3.1 (GOFS 3.1). In both ACNFS and GOFS 3.1, observations of satellite-derived sea surface temperature, ice concentration and ice edge plus in situ data are assimilated via the Navy Coupled Ocean Data Assimilation System (NCODA). However, the present configuration does not assimilate in situ profile observations that sample too little of the water column relative to the ocean depth. This includes the University of Washington Upper Temperature of the polar Oceans (UpTempO) buoys, which sample to a maximum depth of 60 m or shorter in shallow shelf areas. In this study we compare results from the present ACNFS configuration to unassimilated in situ Arctic Ocean observations such as UpTempO buoy observations. And we quantify the impact of assimilation of these same, previously un-assimilated Arctic Ocean observations on short-term Arctic Ocean forecasts.

Tremblay, Bruno: McGill University, bruno.tremblay@mcgill.ca, Professor

The dependence of energy dissipation and sea-ice mechanical properties on spatial resolution in a viscous-plastic model

We present sea ice kinetic energy budgets to quantify how the mechanical strength properties of sea ice should be modified as the spatial resolution is increased. To this end, we study two highly idealized model domains where en- ergy dissipation associated with shear and axial (ridge/lead building) deforma- tion can be analyzed independently. We find that when pure shear deformation is present, the energy dissipated through friction decreases as the spatial resolu- tion of the model is increased and the simulated sea-ice drift speed approaches that of the analytical solution. Increasing spatial resolution leads to a localiza- tion of shear deformation along the domain boundaries effectively increasing the area over which energy is input by the wind which is not compensated for by frictional shear dissipation. For instance at 40 km spatial resolution, 64% and 29% of the input power is dissipated through shear deformation and water drag respectively, while at 5 km spatial resolution 54% and 43% of the input power is dissipated by the respective processes. The result is a 64% increase in the domain total sea-ice kinetic energy and a 32% increase in the mean sea-ice drift speed when the spatial resolution is increased from 40 km to 5 km. This implies that the agreement between simulated sea-ice drift and observations may deteri- orate due to increased model resolution if the sea-ice mechanical properties are not adjusted. This is contrary to what is implicitly assumed in the community, that higher resolution simulations are in general more accurate. In convergence, the mean kinetic energy and potential energy do not depend meaningfully on the spatial resolution. In this case, the structure of the thickness and concen- tration fields effectively sets the velocity gradient near the boundary provided that the plastic deformation wave associated with the ridge building process is resolved.

von Appen, Wilken-Jon: Alfred Wegener Institute Bremerhaven, wilken-jon.von.appen@awi.de, Research Scientist/Dr.

Observations of Atlantic Water subduction below Polar Water at a submesoscale front in Fram Strait

Atlantic Water flows northward in the West Spitsbergen Current and is still present at the surface there. Some of the Atlantic Water flows northward around Svalbard into the Arctic Ocean. The other part recirculates westward, and is eventually transported southward in the East Greenland Current. In central Fram Strait Atlantic Water is found below water of polar origin, which often carries sea-ice with it. Baroclinic instability and mesoscale eddies have been suspected to contribute to the subduction of the Atlantic Water below Polar Water. Here we present submesoscale resolving observations collected at a front in Fram Strait in summer 2017. Underway CTD data combined with shipboard ADCP measurements along 5 parallel cross-frontal sections allow for the calculation of potential vorticity and reveal the full dynamic structure of the front. We use an eddy resolving numerical model to support our interpretation.

Our interpretation is that a strong along-frontal jet exceeding 0.5m/s leads to an ageostrophic secondary circulation with a downwelling component in the Atlantic Water and an upwelling component in the Polar Water. This achieves the subduction of AW below PW and the energetic circulation also leads to mixing between the two water masses. The secondary circulation also leads to surface velocities which advect sea-ice to the frontal location which resulted in a long (~50km) narrow (~500m wide) ice tongue. This ice tongue makes the fronts visible in satellite radar imagery. Observations from a second front and satellite radar imagery suggest that, at least in summer, such fronts may be common features in central Fram Strait with implications for the representation of the recirculation in numerical models

Wang, Qiang: Alfred Wegener Institute (AWI) Helmholtz Center for Polar and Marine Research, Germany, Qiang.Wang@awi.de, (research scientist)

Linkage of the Arctic Ocean to the North Atlantic in two model simulations

The Arctic Ocean is the northern terminate of the North Atlantic Current, which carries warm saline Atlantic Water through the Nordic Seas and penetrates into the mid-depth of the Arctic Ocean. It is recently observed that the ocean condition in the eastern Eurasian Basin is becoming similar to that in the Atlantic-impacted western Eurasian Basin, a process called Arctic Atlantification. This might imply that the Arctic Ocean starts to be in a new climate state. In this work we will assess two model simulations to identify the linkage of the Arctic Ocean to improved model representation of the North Atlantic Ocean. The two simulations have very similar configurations including similar model resolution inside the Arctic Ocean (about 4 km). Outside the Arctic Ocean, however, one simulation has mesoscale-eddy resolving resolutions in mid and low latitudes, while the other has a nominal resolution of about 1 degree. Both simulations are carried out by using an unstructured-mesh ocean sea ice model, which facilitates to use variable resolution to realize locally eddy resolving. We will test one hypothesis: The North Atlantic can be more realistically simulated by using high (eddy resolving) resolution, which can further improve the simulation of the Arctic Ocean.

Waterman, Stephanie: University of British Columbia, swaterman@eoas.ubc.ca, Assistant Professor

Turbulent dissipation and mixing rates in the Canadian Arctic from glider-based microstructure measurements

In situ measures of turbulence in the Arctic Ocean are rare, but critically important for informing the representation of ocean mixing rates in ocean and climate models. We present new observations consisting of 340 quasi-vertical turbulent microstructure profiles of shear and temperature variance, alongside profiles of finescale temperature and salinity in the Amundsen Gulf region of the Canadian Arctic. The measurements were collected over two weeks by an autonomous glider in August 2015, and they represent one of the densest microstructure sampling schemes in the Arctic to date. Further they encompass the most prominent features of the Arctic water column, including the warm Atlantic water layer at depths below 250 m, the halocline between the Pacific and Atlantic water layers, and the surface mixed layer which exhibits a strongly stratified base. We use these observations to characterize the variability of turbulent dissipation rates and inferred turbulent mixing rates in both space and time. We show that these rates vary significantly across four orders of magnitude, but are generally very low. We find mixing between Atlantic- and Pacific-origin water tends to be inhibited by the strong stratification.

Wekerle, Claudia: Alfred Wegener Institute, Claudia.Wekerle@awi.de, PhD Student

Eddy dynamics and properties in the Fram Strait

The Fram Strait is the deepest and widest gateway connecting the Arctic Ocean with the Nordic Seas and thereby the North Atlantic. It is characterized by strong gradients in temperature and salinity: The warm and salty West Spitsbergen Current (WSC), transporting Atlantic Water (AW) northward, encounters the cold and fresh East Greenland Current (EGC), transporting Polar Water (PW) southward. A fraction of Atlantic Water recirculates in the Fram Strait, and thus reduces the amount of heat that reaches the Arctic Ocean. The Fram Strait is a region rich of eddies. They are shed from the WSC, and thus contribute to the AW recirculation. Advection of AW by eddies underneath sea ice accelerates ice melting.
Here we present a simulation carried out with the global Finite Element Sea-ice Ocean Model (FESOM), applying eddy-resolving resolution in the wider Fram Strait (1 km). Mooring measurements conducted for decades in the Fram Strait are used to assess the model performance. In particular, power spectral density of simulated and observed temperature and meridional velocity in the WSC reveal that the model is capable to represent both lower and higher frequency signals. We apply an eddy tracking algorithm to identify eddies and investigate their properties (proportion of anticyclonic to cyclonic eddies, their size, generation sites, lifetime and drift patterns). It is difficult to investigate the properties of eddies in the Fram Strait from satellite altimetry products due to the presence of sea ice and the small scales of eddies indicated by very small Rossby radius of deformation there. Eddy-resolving model simulations thus provide a valuable and necessary tool to gain knowledge about eddy properties and dynamics.

Weijer, Wilbert: Los Alamos National Laboratory, wilbert@lanl.gov, Staff scientist

The HiLAT project: an update

HiLAT (High-Latitude Application and Testing of Global and Regional Climate Models) is a project funded by the Department of Energy. Our strongly interdisciplinary team of scientists from Los Alamos (LANL) and Pacific Northwest (PNNL) National Laboratories is collaborating with academic partners to improve our understanding of high-latitude climate processes and feedbacks. In this presentation I will give an overview of the HiLAT project and the progress we made in our diverse research activities.

Williams, James: NASA GISS, jwilli@mit.edu, Postdoc

Constraining the yield strength of Arctic sea ice with NASA's IceBridge observations

In the standard Viscous-Plastic sea-ice model, the slope of a ridge is set by the ratio of the sea-ice compressive yield strength (P*) and the surface wind stress acting on the ice. Thus, through the use of observed sea-ice thickness data from NASA's operation IceBridge and the observed (reanalysis) wind fields, one can estimate the compressive yield strength of geophysical sea ice. Such comparisons between observations and model simulations provides a novel methodology for choosing and validating an appropriate sea-ice rheology and strength parameterization for regional and global models. Furthermore, this type of analysis allows for constraining uncertainties with respect to the yield criteria of Arctic sea ice. We present here preliminary results of such a comparison and welcome feedback/suggestions.

Woodgate, Rebecca: University of Washington, woodgate@apl.washington.edu

The Changing Bering Strait - recent warming, freshening and flux increases from observations, and the long-sought structure of the "pressure head" forcing, as elucidated by GRACE ocean bottom pressure data

R. Woodgate and C. Peralta-Ferriz

Recent data from the Bering Strait mooring program show remarkable results:

1) significant increasing trends in annual mean fluxes of volume (to 1.2Sv), heat (to 5x10^20J, relative to -1.9°C) and freshwater (to 3500km^3, relative to 34.8psu) between 1990 and present, (but no significant trends in the properties of the Alaskan Coastal Current);

2) a dramatically warm 2016/2017 winter with mean June 2017 temperatures ~3°C warmer than climatology; the strait warming 15 days earlier than climatology and 30 days earlier than any previous recorded year; and waters above freezing remaining in the strait into January 2017 (~20 days later than in any previous year, ~40 days later than climatology);

3) significant winter freshening trends, with winters 2015/2016 and 2016/2017 both ~1psu fresher than climatology.

By estimating the seasonally varying contributions of the Alaskan Coastal Current and stratification from in situ and satellite data, we propose a new 2000s seasonal climatology for volume, heat and freshwater transports, which has an annual mean of 1.0±0.05Sv, compared to the prior climatology of 0.8Sv±0.1Sv, the change being due to change in the flow properties, not change in the methodology.

Using NCEP wind data, we extract the wind-driven component of the flow, showing the summer Bering Strait throughflow to be only poorly related to the wind forcing and instead to be dominantly driven by the far-field "pressure-head' forcing, the component that appears to be responsible for the decadal increasing trends observed.

By comparing the pressure head portion of the flow with GRACE ocean bottom pressure data, we address the ~60 yr old question of what IS the pressure head driving of the flow - identifying the major pattern as low ocean bottom pressure in the East Siberian Sea with a winter component also of high ocean bottom pressure over the Bering Sea Shelf. We show that 70% of the summer Bering Strait flow variability may be explained by variability in the East Siberian Sea bottom pressure pattern, in turn likely related to westward winds along the western Arctic coasts. This suggests that variability in the Pacific inflow to the Arctic is driven primarily by Arctic change, not Pacific change (psc.apl.washinton.edu/BeringStrait.html)

Wright, Nicholas: Thayer School of Engineering, Dartmouth College, Nicholas.C.Wrigth.TH@dartmouth.edu, PhD student

The Open Source Sea-ice Processing (OSSP) Algorithm: A toolkit for the analysis of high resolution optical sea ice imagery

Snow, ice, and melt ponds cover the surface of the Arctic Ocean in fractions that change throughout the seasons. These surfaces control albedo and exert tremendous influence over the energy balance in the Arctic. Increasingly available sub-meter scale resolution optical imagery captures the evolution of the ice and ocean surface state visually, but methods for quantifying coverage of key surface types from raw imagery are not yet well established. Here we present an open-source system designed to provide a standardized, automated, and reproducible technique for processing optical imagery of sea ice. The method classifies surface coverage into three primary categories: Snow and bare ice, melt ponds and submerged ice, and open water. We demonstrate the capabilities of the algorithm by processing imagery from both satellite and aerial platforms and on imagery spanning from spring thaw to fall freeze-up. By providing free access to the software, we hope to encourage future collaborative efforts to integrate direct observations of sea ice surface state with models to better understand the processes and mechanisms that drive surface feature changes on Arctic sea ice.

Yankovsky, Elizabeth: Princeton University, GFDL - USA, eyankovsky@gmail.com (Graduate Student)

Dynamics of dense water formation and transport on the Arctic shelves

The present work is motivated by the role of shelf overflows in setting the thermohaline structure of the Arctic Ocean, thereby contributing to the global overturning circulation, and the need to better parameterize overflow processes in large-scale ocean and climate models. In this study the non-hydrostatic MIT General Circulation Model is applied to investigate dynamics of dense water formation and transport on the Arctic shelves through idealized, high-resolution numerical simulations.

A series of three, progressively complex model setups are examined: two-dimensional without rotation, two-dimensional with rotation, and three-dimensional with rotation. All setups feature a continental shelf region that experiences constant negative buoyancy forcing applied in the form of a negative heat flux and positive salt flux at the surface; however, the three model configurations produce drastically different dynamics. In the 2D nonrotating case, the plume of dense shelf water simply propagates down the continental slope until attaining a neutral buoyancy level – typically around 200m, but varying with forcing magnitude – and then propagates horizontally offshore along this level. In the 2D rotating case, the dense water undergoes geostrophic adjustment and is laterally confined to the shelf/forcing region, attaining a greater density anomaly than the nonrotating case. Bottom Ekman dynamics breaks the geostrophic balance leading to the geostrophic jet and dense water within the bottom frictional layer descending to the bottom of the continental slope, at 2500m. Regions of negative potential vorticity produce symmetric instabilities, which act to align angular momentum and density isolines by mixing dense water in the bottom frictional layer away from the continental slope. In the 3D rotating simulations there is a similar process of geostrophic adjustment, in this case broken by formation of baroclinic eddies. Buoyancy forcing parameters as well as topographic features set eddy properties, which in turn govern turbulent mixing and entrainment processes. For typical forcing values baroclinic eddies produce dense water cascades reaching the bottom of the continental slope. When forcing is decreased by an order of magnitude the eddies ventilate primarily the upper 1000m of the water column. Thus, the rotating 2D and 3D simulations highlight two inherently unstable, yet distinct regimes by which dense water may ventilate the deepest portions of the Arctic Ocean.

Yang, Chao-Yuan: University at Albany – SUNY, cù114@albany.edu, PhD student

Assessment of Arctic and Antarctic Sea Ice Predictability in CMIP5 Decadal Hindcasts

This work examines the ability of coupled global climate models to predict decadal variability of Arctic and Antarctic sea ice. We analyze decadal hindcasts/predictions of 11 CMIP5 models. Decadal hindcasts exhibit a large multi-model spread in the simulated sea ice extent, with some models deviating significantly from the observations as the predicted ice extent quickly drifts away from the initial constraint. The anomaly correlation analysis between the decadal hindcast and observed sea ice suggests that in the Arctic, for most models, the areas showing significant predictive skill become broader associated with increasing lead-times. This area expansion is largely because nearly all the models are capable of predicting the observed decreasing Arctic sea ice cover. Sea ice extent in the north Pacific has better predictive skill than that in the north Atlantic (particularly at a lead-time of 3-7 years), but there is a re-emerging predictive skill in the north Atlantic at a lead-time of 6-8 years. In contrast to the Arctic, Antarctic sea ice decadal hindcasts do not show broad predictive skill at any time scales, and there is no obvious improvement linking the areal extent of significant predictive skill to lead-time increase. This might be because nearly all the models predict a retreating Antarctic sea ice cover, opposite to the observations. For the Arctic, the predictive skill of the multi-model ensemble mean outperforms most models and the persistence prediction at longer time scales, which is not the case for the Antarctic. Overall, for the Arctic, initialized decadal hindcasts show improved predictive skill compared to uninitialized simulations, although this improvement is not present in the Antarctic.

Yaremchuk, Max: Naval Research Laboratory - USA, max.yaremchuk@nrlssc.navy.mil (Oceanographer)

Gaussianized 2dVar assimilation of ice concentration into CICE model

Results of numerical experiments assimilating SSMI/IMS data into the HYCOM-driven CICE model are presented. To remove inconsistency between the Gaussian assumptions underlying the 2dVar algorithm and non-Gaussian nature of ice concentration (IC) errors, the respective innovations are gaussianized prior to the analysis. The inverse (degaussianization) transform is computed at the analysis step and exploits similarity between the PDFs of IC innovations and increments. Gaussianization uncertainties are taken into account by an additional 2dVar algorithm optimizing the estimate of the background error variance with respect to the innovations obtained after the analysis. Numerical experiments with 2dVar assimilation of SSMI/IMS observations acquired in September-December 2015 in the Beaufort Sea demonstrate 5-10% improvement of the 24-hour forecast skill compared to the operational runs executed without gaussianization. An additional set of experiments was conducted to assess the impact of anisotropic IC covariance generated by the background ice velocity field. The respective forecast skill improvements were 1-2% in the gaussianized mode and 4-6% without gaussianization.

Zampieri, Lorenzo: AWI - Germany, lorenzo.zampieri992@gmail.com (PhD Student)

Verification of Seasonal and Sub-seasonal Sea Ice Forecasts

Sea ice forecasts are becoming a demanding need since human activities in the Arctic are constantly increasing and this trend is expected to continue. Forecast system development needs to be guided by verification metrics that quantify skill in an appropriate way. Here we apply different verification metrics to real sea ice forecasts to study the behavior of the metrics and to quantify potential predictive skills of the forecasts systems, focusing on the sea ice edge position and on sub-seasonal to seasonal time scales. The employed metrics are the pan-Arctic sea ice extent (SIE) and area (SIA), the Integrated Ice Edge Error (IIEE), the Spatial Probability Score (SPS), and the Modified Hausdorff Distance (MHD). While the first two metrics evaluate a single integrated quantity, the latter three assess the spatial distribution of the ice cover. Forecasts are verified against the high resolution AMSR-E and AMSR2 89 GHz sea ice concentration products provided by the University of Bremen and against models own analyses, which are based on the initial state of the forecasts control run. Sea ice forecast products from various research institutes and operational centers are analyzed, in particular those collected within the S2S (Sub-Seasonal to Seasonal) Prediction Project. The forecast systems are characterized by quite different features with regard to the spatial resolution and the complexity of the forecast model, the number of ensemble members and the forecast length. The broad pool of models allows a comprehensive analysis of the metrics' behavior in different situations, highlighting strengths and weaknesses of the models and of the metrics themselves.

Zhao, Jiechen: Ocean University of China; National Marine Environmental Forecasting Center - China, zhaojiechen@outlook.com (PhD Student)

The Inter-comparison and Assessment of Seven Satellite Sea Ice Concentration Datasets in Arctic

The rapid decrease of Arctic sea ice makes the normalized commercial shipping through Arctic Passages possible. The accurate sea ice concentration (SIC) data is the very important basis for Arctic shippings and numerical simulation. In this paper, seven PM-SIC datasets released by Bremen University, NSIDC and EUMETSAT was intercompared and assessed using the ship-based OBS-SIC during the 5th CHINARE Arctic Northeast Passage cruise from July to September, 2012.

Totally 604 pairs OBS-SIC from around 20 days in-ice cruise are used for evaluation here. To avoid the bias from the daily changes of sea ice and different spatial resolutions, a method to calculate daily mean PM-SIC and OBS-SIC for comparison is used in this paper, refered to the similar evaluation work in Antarctica (Beitsch et al., 2015). MODIS images are also used to evaluate the distribution of sea ice near the continent, narrow strait and island.

Results show that, seven satellite datasets have the similar pattern of large sea ice distribution, but are quite different near continent, island and strait. MASAM sucessfully detect the small ice floe area near Poluostrov Taymyr on July 25, 2012 and near Ostrov Vrangelya on September 1, 2012, but others fails. Latitude mean comparison show that seven PM-SIC have high similar skills to detect that the grid was totally water or sea ice, but differ largerly about how much percent of sea ice is in the ice grid. Quantitatively evoluation by comparing with OBS-SIC show that AMSR2/ASI, AMSR2/Bootstrap, SSMIS/ASI and SSMIS/Bootstrap perform well, but SSMIS/NT and MASAM perform badly. AMSR2/ASI have the smallest bias of 1% and RMSE of 11%, but SSMIS/NT underestimate the SIC largely with mean bias of -15% and RMSE of 21%. AMSR2/ASI has a higher spatial resolution among the well-performed group, and more important it is updated near real time. High resolution and timely updated is the most important factor for operational ice service, which make AMSR2/ASI best choice for real-time shipping-guide and operational sea ice forecasting.

Zhao, Mengnan: Yale University, mengnan.zhao@yale.edu, PhD student

Energy transfer in the Beaufort Gyre

Energy transfer associated with the large-scale Beaufort Gyre circulation and dissipation is examined. We begin by investigating where Available Potential Energy (APE) is most likely converted to Eddy Kinetic Energy (EKE) through calculation of a measure of baroclinic instability (the Eddy growth rate) from hydrographic measurements. These results are set in context with the observed evolution of APE and distribution of mesoscale eddies. We show an intensified eddy field in response to increased basin APE. Kinetic energy inferred from velocity measurements sampled by the four Beaufort Gyre Observing System moorings is also examined. We partition EKE into dynamic modes calculated from background mean stratification profiles. The ubiquitous halocline eddies are found to be characterized by the first and second baroclinic modes; EKE is concentrated in these modes. The reason and implications for this are examined.

Zhong, Wenli: University of Washington, wlzhong@uw.edu

Greater role of geostrophic currents on Ekman dynamics in the western Arctic Ocean as a mechanism for Beaufort Gyre stabilization

Seven different methods, with and without including geostrophic currents, were used to explore Ekman dynamics in the western Arctic Ocean for the period 1992–2014. Results show that surface geostrophic currents have been increasing and are much stronger than Ekman layer velocities in recent years (2003–2014) when the oceanic Beaufort Gyre (BG) is spinning up in the region. In comparison with satellite observations, the new methods that include geostrophic currents result in more realistic Ekman pumping velocities than a previous iterative method that does not consider geostrophic currents which overestimates Ekman pumping velocities by up to 52% in the central area of the BG over the period 2003–2014. This suggests that including geostrophic currents is crucial in realistically representing the large-scale Ekman dynamics in the region, particularly so when the BG is spinning up. When the BG is spinning up as seen in recent years, geostrophic currents become stronger, which tend to modify the ice-ocean stress and cause an Ekman divergence in the southern Canada Basin. This is a mechanism we have identified to play an important and growing role in stabilizing the Ekman convergence and therefore the BG in recent years. This mechanism can be used to explain three scenarios describing the interplay of changes in wind forcing, sea ice motion, and geostrophic currents that control the variability of the Ekman dynamics in the western Arctic Ocean during 1992–2014.