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The role of ocean heat transport on rapid sea ice declines in the Community Earth System Model Large Ensemble

***Gabriel Auclair,* McGill University**

Many climate models predict future periods of rapid sea ice and decline in the Arctic. These events are linked with anomalous northward Ocean Heat Transport (OHT). Using the Community Earth System Model Large Ensemble (CESM-LE), we find that the pathway by which the OHT enters the Arctic (Barents Sea Opening (BSO), Fram Strait or Bering Strait) is key to this link with the rapid declines. The interaction between OHT and sea ice happens mainly over continental shelves where the BSO and Bering Strait OHTs are strongly correlated with basal melt, ice-ocean heat flux, absorbed short wave radiation in the ocean and ice growth. The Bering Strait OHT is linked to more rapid declines than the BSO OHT, presumably because of the broader Eurasian shelf. No clear link is found between rapid declines and the Fram Strait OHT, which enters the Arctic Ocean at depth, except when the rapid decline is also linked to another OHT. In total, 64 of the 79 rapid declines in CESM-LE are linked with anomalous OHT. When the September Sea Ice Extent (SIE) before the rapid decline is located only over deep basins in the central Arctic, we observe a decrease in basal melt during the decline. We hypothesize that this is due to an enhanced stratification that reduces heat transfer between the ocean and the ice. The ice-atmosphere heat flux anomalies are more strongly correlated with the sea ice concentration anomalies over the deep basins in the 21st century than the ice-ocean heat flux anomalies. Our results suggest that OHT are causing rapid sea ice declines mostly when the SIE is large enough to cover the continental shelves and that the atmosphere is the main driver when the initial SIE is located only over the deep basins.

Coupled wave-ice interactions in the marginal ice zone in simulations with a floe-size distribution

Cecilia Bitz, **University of Washington**

TBD

The role of persistence in sea ice predictability across GCMs

Edward Blanchard-Wrigglesworth, University of Washington

General circulation models have been amply used to quantify Arctic sea-ice predictability. While models show some agreement in the general tendency of predictability loss with increasing forecast lead times, there are significant differences in its magnitude and timing. We show that inter-model differences in predictability are linked to inter-model differences in the persistence timescales of sea-ice anomalies that are unique to each model. Since previous work has shown that sea-ice persistence in a single model simulation fluctuates between periods of high and low persistence that may last several years, we assess whether initial-value predictability is dependent on the persistence state of the initial conditions. We find that forecast spread predictability is not significantly different across high/low persistence periods, suggesting that predictability may be robust within a constant climate mean state. Our results also imply that annual periods of high/low persistence are not predictable and are mainly forced by the atmosphere rather than the ice-ocean system.

Improved seasonal forecasts of summer sea ice extent using assimilation of CryoSat-2 thickness

***Ed Blockley,* Met Office, UK**

Seasonal predictions at the Met Office are made using the GloSea5 coupled forecasting system which has contributed September sea ice predictions to SIPN since its implementation in 2013. The GloSea seasonal prediction system is run daily at the Met Office and uses the Nucleus for European Modelling of the Ocean (NEMO) model coupled to the Los Alamos sea ice model (CICE). The ocean and sea ice components of GloSea are initialised using analysis fields from the FOAM ocean-sea ice analysis and forecast system which routinely assimilates sea ice concentration along with various ocean quantities (satellite and in-situ SST, satellite SLA, in-situ profiles of temperature and salinity). However, sea ice thickness is not yet assimilated - which is also true for most operational ocean analysis and seasonal forecasting systems.

Many studies have suggested that initialisation of winter sea ice thickness could lead to improved prediction of Arctic summer sea ice. Here we directly assess the impact of winter sea ice thickness initialisation on the skill of seasonal summer forecasts by assimilating CryoSat-2 thickness data into the GloSea coupled seasonal forecasting system. We show a significant improvement in predictive skill of Arctic sea ice extent and ice-edge location for forecasts of September Arctic sea ice made from the beginning of the melt season. These improvements in sea ice cover also lead to further improvement of near-surface air temperature and pressure fields across the region. A clear relationship between modelled winter thickness biases in GloSea and summer extent errors is identified which supports the theory that Arctic winter thickness provides some predictive capability for summer ice extent and further highlights the importance that modelled winter thickness biases can have on the evolution of forecast errors through the melt season.

Winter preconditioning of the minimum sea ice extent in the Laptev Sea

***Charles Brunette*, McGill University**

In this work, we explore the use of wintertime coastal divergence of sea ice in the Eurasian sector as a regional predictor for the minimum sea ice extent (Brunette et al. (2018), submitted). Williams et al. [2016] propose winter dynamic preconditioning as a predictor for the pan-Arctic minimum sea ice extent. Coastal divergence of sea ice from the Eurasian coastlines leads to the formation of coastal polynyas, where new ice formation occurs 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 of the same amount as the climatological summer melt (Nikolaeva & Sesterikov [1970]). Consequently, anomalies of late winter coastal divergence are anti-correlated to anomalies of the following September minimum SIE, i.e. the more late winter coastal divergence, the less sea ice in September. We study this mechanism at a regional scale in the Laptev Sea where ice motion is on average divergent during the winter. We use the Lagrangian Ice Tracker System (LITS), forced with sea ice drifts from the Polar Pathfinder V3 (Tschudi et al. [2016]) to track displacement of sea ice and explicitly identify regions of coastal divergence. In the Laptev Sea, the strongest negative correlation with September sea ice extent is obtained when considering coastal divergence occurring between February and May (r=-0.63). Also, a slope of m=-1.6 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.

Regional Arctic sea-ice prediction: Potential versus operational seasonal forecast skill

Mitch Bushuk, **Geophysical Fluid Dynamics Laboratory (GFDL),**

National Oceanic and Atmospheric Association (NOAA)

Seasonal predictions of Arctic sea ice on regional spatial scales are a pressing need for a broad group of stakeholders, however, most assessments of predictability and forecast skill to date have focused on pan-Arctic sea-ice extent (SIE). In this work, we present the first direct comparison of perfect model (PM) and operational (OP) seasonal prediction skill for regional Arctic SIE within a common dynamical prediction system. This assessment is based on two complementary suites of seasonal prediction ensemble experiments performed with a global coupled climate model. First, we present a suite of PM predictability experiments with start dates spanning the calendar year, which are used to quantify the potential regional SIE prediction skill of this system. Second, we assess the system's OP prediction skill for detrended regional SIE using a suite of retrospective initialized seasonal forecasts spanning 1981-2016. In nearly all Arctic regions and for all target months, we find a substantial skill gap between PM and OP predictions of regional SIE. The PM experiments reveal that regional winter SIE is potentially predictable at lead times beyond 12 months, substantially longer than the skill of their OP counterparts. Both the OP and PM predictions display a spring prediction skill barrier for regional summer SIE forecasts, indicating a fundamental predictability limit for summer regional predictions. We find that a similar barrier exists for pan-Arctic sea-ice volume predictions, but is not present for predictions of pan-Arctic SIE. The skill gap identified in this work indicates a promising potential for future improvements in regional SIE predictions.

Verification of sea-ice prediction by using distance measures

Barbara Casati, **Meteorological Research Division,**

Environment and Climate Change Canada (ECCC)

Sea-ice is characterized by a coherent spatial structure, with sharp discontinuities and linear features (e.g. leads and ridges), the presence of spatial features, and a multi-scale spatial structure (e.g. agglomerates of floes of different sizes). Traditional point-by-point verification approaches do not account for this complex spatial structure and the intrinsic spatial correlation existing between nearby grid-points. This leads to issues (such as double penalties), and an overall limited diagnostic power (e.g. traditional scores are insensitive to distance errors).

This work explores the use of binary image distance measures of the Hausdorff and Baddeley family for the verification of sea-ice extent and sea-ice edge. The metrics are illustrated for the Canadian Regional Ice Ocean Prediction System evaluated against the Ice Mapping System analysis. The distance measures account for the sea-ice coherent spatial structure, are sensitive to the overlapping and similarities in shape of observed and predicted sea-ice extent: they reveal to be a robust and suitable set of verification measures, complementary to the traditional categorical scores. Moreover, these measures can provide distance errors, e.g. of observed versus predicted sea-ice edge, in physical terms (i.e. km), thereby being informative and meaningful for user-relevant applications.

Impact of sea ice sources on calibrating a wave-ice interaction model

***Sukun Cheng,* Clarkson University**

Because of the interaction between ocean wave and sea ice, reliable models for wave propagation in the ice-covered region is critical to sea ice morphology. We present calibration of a viscoelastic type wave-in-ice model with wave, wind, and ice data collected from the Beaufort and Chukchi seas in the autumn of 2015. The data were from multiple sources of in-situ and remote sensing measurements in the marginal ice zone during the ice advance season. We assessed the influence of various ice sources in the model calibration and compared wave hindcasts using the ocean wave model WaveWatch III with in-situ measured wave data in the field studied region. This analysis will be useful in the model calibration and wave forecasts in the interior pack ice field in the Arctic Ocean.

What Predictability for Polar Sea Ice at the Subseasonal Time Scale?

***Matthieu Chevallier,* Centre National de Recherches Météorologiques (CNRM),**

Météo France/CNRS

One of the purpose of YOPP is to enhance predictive capabilities in the polar regions and beyond from hours to season. There is a growing demand for sea ice forecast on subseasonal (from 1 week to 2 months) time scale, which is the relevant time scale for operational needs. Thus far the role of sea ice on subseasonal climate predictability is not well understood, and the effort of the scientific community has mostly targeted seasonal-to-decadal predictability. This presentation is a summary of a review conducted within the projects Subseasonal-to-Seasonal (S2S), Polar Prediction Project (PPP) and the European project APPLICATE. Using a variety of sea ice observations, model reconstructions and reanalyses, the memory of the main descriptors of the sea ice state has been quantified. Persistence of the sea ice areal properties emerges as the primarily source of sea ice subseasonal predictability in both polar oceans, strongly dependent on season. Further memory can be expected from re-emergence mechanisms implying processes internal to sea ice and coupling with the atmosphere and the ocean. Predictive skill of some S2S models is also presented. Given the role of sea ice as a unique boundary conditions for the atmosphere, this study provides strong reasons for a possible role of sea ice on atmosphere subseasonal predictability. With this presentation, we would like to encourage scientists to further explore the S2S database with a polar perspective, as part of the YOPP modelling effort.

Overview of the CPC Sea Ice initialization System (CSIS) and its use in experimental sea ice forecasting at the NOAA Climate Prediction Center

Thomas Collow, **INNOVIM, LLC/NOAA Climate Prediction Centre**

Beginning in 2015, the NOAA Climate Prediction Center (CPC) began issuing seasonal sea ice outlooks to the NWS Alaska Region based on an experimental extended-range forecast system modified from the NCEP operational climate forecast system version 2 (CFSv2). Unlike the operational CFv2, which is initialized from the Climate Forecast System Reanalysis (CFSR), the CPC experimental forecast system is initialized with sea ice from the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS). The experimental outlooks saw a marked improvement over the operational CFSv2, and therefore will continue to be produced. While PIOMAS data provides an adequate representation of Arctic sea ice distribution, there are disadvantages in using the data to initialize our system namely, i) consistency of the ocean model (PIOMAS and CFSv2 use different ocean models with different sea ice thickness categories that require interpolation), and ii) reliance on an outside source for data in an operational environment. As a result, CPC has developed an in-house sea ice analysis product for initializing sea ice outlooks, known as the CPC Sea ice Initialization System (CSIS). Like PIOMAS, CSIS assimilates sea ice concentration data. Both systems do not assimilate sea ice thickness, but experiments to assimilate sea ice thickness information into CSIS are planned. For this presentation, we will provide an overview of the development of CSIS, in addition to presenting results from hindcasts and forecasts with the new system, along with comparisons to CFSR and PIOMAS initializations.

An assessment of regional sea ice predictability in the Arctic ocean

Ruben Cruz-Garcia, **Barcelona Supercomputing Center (BSC-CNS)**

Arctic sea ice plays a central role in Earth climate. Its changes on seasonal-to-interannual timescales impact ecosystems, populations and a growing number of stakeholders. A prerequisite to achieve better sea ice predictions is a better understanding of the underlying mechanisms of sea ice predictability. Previous studies have shown that sea ice predictability depends on the parameter (area, extent, volume), region, initial and target dates. Here we investigate seasonal-to-interannual sea ice predictability in so-called “perfect model” 3-year-long experiments run with the EC-Earth 2.3 climate model initialized in early July. Consistently with previous studies, robust mechanisms of reemergence are highlighted, i.e. increases in autocorrelation of sea ice properties after an initial loss. We find that Arctic regions can be classified according to three distinct regimes. Central Arctic drives most of the pan-Arctic sea ice volume persistence. In peripheral seas, we find trivial predictability of sea ice area in winter but low predictability throughout the rest of the year, due to the particularly unpredictable sea ice edge location. The Labrador Sea stands out as a remarkable region, with sea ice predictability extending up to 1.5 years if oceanic conditions upstream are known.

Short-term sea ice prediction for Arctic shipping

***Liyanarachchi Waruna Arampath De Silva,* University of Tokyo**

Precise prediction of short-term sea ice distribution is the major factor when it comes to safe and efficient navigation in the Arctic Ocean. A high-resolution (about 2.5 km) ice-ocean coupled model is developed for forecasting the short-term sea ice distribution along the Northern sea route. The experiment was run from 05 May 2015 to 20 November 2015. The atmospheric forcing data used for the model was European Center for Medium-Range Weather Forecast Interim reanalysis data. The correlation score of ice–edge error and sea ice concentration distribution quantifies forecast skill and skill scores are computed from 05 May 2015 to 20 November 2015. The average forecast skill of ice-edge error in the ice-ocean coupled model is 10.09 km with the 15% thresholds of ice concentration for the ice edge. That is in good agreement with the requirement of an operational ice navigation system (10 km).

Spatiotemporal Bias Correction of Sea Ice Forecasts

Hannah Director, **University of Washington**

Physical models of sea ice have skill in forecasting the concentration of sea ice at different spatial locations; however, they are not without error. Many of these errors exhibit spatial and temporal patterns, so statistical techniques can be used to correct them. In this talk, I will introduce a bias correction method called contour-shifting that can be applied to the sea ice edge contour. This method anticipates and corrects systematic errors in the location of the sea ice edge contour. I will illustrate the potential increase in accuracy that can be gained from contour-shifting by applying this technique to model output from the CM2.5 Forecast-Oriented Low Ocean Resolution model produced by NOAA's Geophysical Fluid Dynamics Laboratory and NASA Bootstrap Sea Ice Concentrations from the Nimbus-7 SMMR and DMSP SSM/I-SSMI satellites. For the years 2001-2013, contour-shifting reduces the area incorrectly categorized as being above or below the 15% concentration threshold by an average of 330,000 square kilometers, or 21%. In the talk, I will also discuss open-source software that allows contour-shifting to be easily applied to outputs of any sea ice model in the Arctic.

Multi-Model Calibrated Probabilistic Seasonal Forecasts of Regional Arctic Sea Ice Coverage

***Arlan Dirkson,* Université du Québec à Montreal**

This presentation will describe the extension of a novel methodology for making probabilistic forecasts of local sea ice coverage to a multi-model framework. Such probabilistic forecasts that represent uncertainty can be essential for end-users who want to quantify risk and make decisions taking forecast uncertainty into account. As individual models contain their own errors from a variety of sources, multi-model ensembles tend to produce more skillful forecasts. Our procedure consists of fitting single-model ensemble forecasts of local sea ice concentration (SIC) to a well-suited probability distribution, and calibrating these distributions using trend-adjusted quantile mapping (TAQM). Such a procedure can be used to make calibrated forecasts of the spatial SIP quantity -- describing the probability of local sea ice coverage based on a minimum 15% SIC threshold -- used for the annual Sea Ice Outlook. Here, we present on the utility of this approach by combining calibrated outputs from ensemble forecasts from CanCM3 and CanCM4, two fully-coupled dynamical climate models, which together formulate the Canadian Seasonal to Interannual Prediction System. We focus specifically on September forecasts of SIP initialized on the 1st of June, July, and August. To place our approach of calibrating individual model forecasts and combining their calibrated output into context, probabilistic forecast skill is compared against simpler approaches such as the direct averaging of raw model output.

Using Complex Networks to Advance our Understanding of the Polar Climate System

***Will Gregory,* University College London (UCL)**

TBD

Subseasonal Polar forecasting using the U.S. Navy Earth System Model (NESM)

David Hebert, **Naval Research Laboratory**

The U.S Navy is developing the Navy Earth System Model (NESM) that is a fully coupled atmosphere (NAVGEM, NAVy Global Environment Model) /ocean (HYCOM, HYbrid Coordinate Ocean Model) /sea ice (CICE, Community Ice CodE) forecasting system. Currently NESM is participating in the North American Multi-Model Ensemble Subseasonal eXperiment (SubX), where each week the system provides 4 member time-lagged 45 day ensemble forecasts to Climate Prediction Center forecasters at NCEP. This work has been leveraged to provide the U.S. National Ice Center with long term sea ice forecasts. In addition, we plan to make NESM long term forecasts available to the Year of Polar Prediction (YOPP). In this presentation, an overview of NESM will be provided, including an ice edge error analysis comparison to the U.S. Navy pre-operational Global Ocean Forecast System (GOFS) 3.1.

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

Sean Horvath, **University of Colorado Boulder**

National Snow and Ice Data Centre (NSIDC)

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

Sub-seasonal to seasonal forecasts of Arctic sea ice in 2017 and 2018 using Regional Arctic System Model (RASM)

***Samy Kamal,* Naval Postgraduate School**

A major effect of the Arctic's amplified response to global climate change has been the accelerated decline of sea ice cover, both in terms of area as well as thickness and volume. Such changes have significant climatic and societal implications, as increasing parts of the Arctic Ocean become seasonally ice free and for longer periods of times. Advanced understanding and modeling of the rapidly changing Arctic system is required to improve prediction of arctic change needed to address increasing demands for environmental intelligence from stakeholders, including native communities, national defense and policy makers, energy, shipping and tourism industries. In this presentation, an approach for using the Regional Arctic System Model (RASM) to dynamically downscale global forecasts is presented and results on sub-seasonal to seasonal sea ice forecasts for 2017-2018 are summarized.

RASM is a fully coupled regional system model consisting of five separate components: the Weather Research and Forecasting (WRF) model for the atmosphere, the Variable Infiltration Capacity (VIC) for the land-hydrology, the Los Alamos National Laboratory Parallel Ocean Program (POP) and Sea Ice Model (CICE), the stream flow routing scheme (RVIC). They all communicate through a flux coupler (CPL7) to exchange fluxes every 20 minutes. WRF and VIC are configured on a 50-km polar stereographic grid and POP and CICE are configured on a 9-km rotated sphere grid.

To create the initial conditions for sub-seasonal to seasonal (S2S) forecasts RASM is forced along its lateral boundaries and in the upper half of the atmosphere with the NCEP Climate Forecasting System Reanalysis (CFSR) from 1979 to the present. This ensures the internal consistency of the initial conditions among all RASM components. S2S ensemble forecasts of sea ice extent, concentration, and thickness are produced for each month of 2017 as well as for September 2018 minimum. Forecasts for 2017 consist of 4 different 28-member ensembles with lead times of 2 weeks, 1, 2, and 3 months. Additionally, 2017 and 2018 sea ice minima in September are forecasted with two extra ensembles each, with lead times of 5 and 6 months. All forecast runs are forced with the NCEP Climate Forecast System Version 2 (CFSv2) after initialization. We use available satellite observations to assess and discuss the skill of forecasts and its dependence on initial conditions, target month, and lead-time.

Data-driven stochastic prediction of regional Arctic sea ice extent

***Dmitri Kondrashov,* University of California, Los Angeles (UCLA)**

Data-adaptive harmonic decomposition (DAHD) and inverse stochastic modeling techniques are applied for characterization and prediction of Arctic Sea Ice Extent (SIE). The DAHD identifies narrowband, spatio-temporal data-adaptive modes over four key Arctic regions. The time evolution of these modes is efficiently modeled and predicted by a set of coupled Stuart-Landau stochastic differential equations. Retrospective forecasts show that resulting multiscale Stuart-Landau model (MSLM) is quite skillful in predicting September SIE; moreover, this approach provided accurate real-time prediction in the submissions into 2016&2017 Sea Ice Outlook. The key success factors are associated with DAHD ability to disentangle complex regional dynamics of SIE by data-adaptive harmonic spatio-temporal patterns that reduce the data-driven modeling effort to elemental inverse models stacked per frequency with fixed and small number of model coefficients to estimate.

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Recent model developments for improving the simulation of landfast ice

***Jean-Francois Lemieux,* Environment and Climate Change Canada (ECCC)**

Due to their low spatial resolutions and the lack of representation of some physical mechanisms such as grounding, sea ice models used to poorly simulate the landfast ice cover. With the increase in spatial resolution of ice-ocean forecasting systems and even of climate models, there is growing interest in better representing the formation, stabilization and break up of landfast ice. We will describe recent model developments to improve the simulation of landfast ice: a modified viscous-plastic rheology and a parameterization describing the grounding or pressure ridges in shallow water. CICE-NEMO pan-Arctic experiments demonstrate that combining these parameterizations notably improves the simulation of the landfast ice cover. Nevertheless, the area of landfast ice is overestimated compared to observations in regions of strong tides. Additional simulations with 13 tidal constituents show that tides clearly decrease the extent of landfast ice in some regions such as the Gulf of Boothia and Prince Regent Inlet. We show that it is mostly due to the increase of the ocean stress at the ice interface that leads to a decrease in the landfast ice extent. Changes in grounding cannot explain this ‘loss’ of landfast ice area.

Subseasonal Forecast Skill over Polar Regions in Three Operational S2S Systems

***Hai Lin,* Environment and Climate Change Canada (ECCC)**

Pentad forecast skill over the polar region in boreal winter is evaluated for the subseasonal to seasonal prediction (S2S) systems from three operational centers: ECMWF, NCEP and ECCC. The former two systems are running with air-sea coupled models, whereas the latter with an atmospheric-only model. One objective of this study is to assess the impact of air-sea coupling on polar subseasonal forecast skill. Previous studies have reported that the ECMWF system has a far better Madden-Julian Oscillation (MJO) forecast skill than the other systems. Whether the MJO skill translates to polar forecast skill is of great interest.

The results indicate that the three systems have comparable forecast skill in surface air temperature, although the air-sea coupled systems perform slightly better than the atmospheric-only system in pentads 3-6. The forecast skill dependence on MJO amplitude and phase is also evaluated.

Multi-week prediction of Arctic sea ice in a coupled ocean–atmosphere model

Yanyun Liu, **Innovim LLC/NOAA Climate Prediction Center**

Skillful Arctic Sea ice prediction is becoming increasingly important because of its societal, industrial and economic impacts over the polar regions and potential influence on the lower-latitude weather and climate variability. Previous Arctic sea ice prediction efforts with general circulation models have primarily focused on the seasonal range. In this work, we evaluate the multi-week forecast skill of Arctic sea ice using the NCEP's Climate Forecast System version 2 (CFSv2). This is likely the first effort to diagnose and assess the skill of multi-week Arctic sea ice prediction from a coupled atmosphere-ocean model. Analysis of a suite of retrospective 45-day forecasts spanning 1999-2015 shows that the CFSv2 captures the general features of sea ice concentration (SIC) variability. The total SIC variability is dominated by interannual variability, which accounts for more than 60% of the total variance. Submonthly variability accounts for about 29% of total variance in December, 20% in March and June, and 12.5% in September. We assess the ability of the CFSv2 to predict the pan-Arctic SIC, as well as regional SIC in nine Arctic regions. It is shown that the prediction skill of SIC is highly region-dependent, e.g., higher prediction skill for the Kara/Barents Sea and lower for the Canadian Archipelago. Overall, the maximum anomaly correlation coefficient (ACC) of SIC for both melt and freeze-up seasons is near the marginal zone and their spatial distribution shows a relationship with the distribution of the variance, i.e., areas of larger variance also have higher ACC. If the ACC of 0.5 is taken as the critical value for skillful prediction, predictability of weekly SIC near the marginal zone is about 5-6 weeks. Prediction skill for Northern Hemisphere sea ice extent (SIE) is above 0.6 for the entire 6 target weeks and has a large contribution from interannual variability.

Toward improved, internally consistent initial conditions for Arctic sea ice prediction at sub-seasonal to interannual time scales

Wieslaw Maslowski, **Naval Postgraduate School**

In this presentation we discuss the challenges and opportunities for Arctic sea ice prediction at timescales from sub-seasonal to interannual (S2I). In particular, we focus on the research paradigm involving the combination of both the initial and boundary value problems. At time scales beyond synoptic, data assimilation of limited information does not improve much the model prediction skill, while Earth System models have rather limited skill in representing Arctic climate, its variability and trends, both in terms of initial or boundary conditions. Those limitations include a coarse model resolution, inadequate parameterizations and unrepresented or missing processes. Likewise, stand-alone global ocean-ice or atmosphere-land models do not include fundamental surface feedbacks at the marine interface, which negates the strongly non-linear coupling, known to be important in polar regions. Finally, a few fully coupled climate models exist with spatio-temporal resolution in the Arctic adequate to represent essential processes and resulting coupling across the interface.

We present results using the Regional Arctic System Model (RASM) to dynamically downscale the NCEP Climate Forecast System Reanalysis (CFSR) from 1979 until present. RASM is a regional coupled climate model developed to better understand and predict the operation of Arctic climate system at daily to decadal time scales. Its pan-Arctic domain is configured at an eddy-permitting (~9km) or eddy-resolving (~2.4km) resolutions for the ice-ocean and 50km or 25km for the atmosphere-land. All RASM components are coupled through the flux coupler every 20 min to provide high temporal resolution. We demonstrate RASM capability in simulating observed climatic seasonal to decadal variability and trends, hence an improved skill in providing realistic and internally consistent initial conditions for S2I sea ice prediction. Selected physical processes and feedbacks will be discussed to emphasize the need for fully coupled climate model, high resolution and fine tuning of sub-grid parameterizations, when changing model resolution. A separate presentation involving RASM for sub-seasonal to seasonal (S2S) prediction forced with NCEP CFS version 2 (CFSv2) global predictions will summarize lessons learned from using RASM to produce sea ice forecasts for all months of 2017 and September 2018.

The importance of temporal consistency for sea ice initialization in seasonal forecasts: Lessons from CanSIPS

William Merryfield, **Canadian Centre for Climate Modelling and Analysis**

The Canadian Seasonal to Interannual Prediction System (CanSIPS) has used two coupled climate models, CanCM3 and CanCM4, to produce the Meteorological Service of Canada's (MSC's) operational seasonal forecasts since late 2011. CanSIPS was one of the first such systems to have an interactive sea ice component. However, because seasonal forecasting of sea ice was not a major focus at the time the system was developed, the initialization of sea ice was treated somewhat simplistically, by nudging sea ice concentration to the HadISST1.1 observational dataset and sea ice thickness to a seasonally-varying model-based climatology. Real time CanSIPS forecasts have predicted implausibly large values for Arctic sea ice extent. This has been traced to three deficiencies in the sea ice initialization: (i) unrealistic trends in the HadISST1.1 concentrations used for the hindcasts, (ii) the absence of trends in initial sea ice thickness, and (iii) different types of source observations for HadISST1.1 and the MSC operational analysis used to initialize sea ice in real time. This presentation will describe how these issues were diagnosed and corrected, leading to a modified version of CanSIPS that had produced improved Arctic sea ice forecasts starting with the 2017 Sea Ice Outlook.

Toward user-relevant monthly to seasonal forecasts of Arctic sea ice: The FRAMS project

William Merryfield, **Canadian Centre for Climate Modelling and Analysis**

TBD

Role of wind stress in the partitioning of Ocean flux between Fram Strait and Barents Sea Opening gates

Bimochan Niraula, **McGill University**

TBD

Sea Ice Predictability and the Alaska Sea Ice Program

***Emily Niebuhr,* National Oceanic and Atmospheric Association (NOAA)**

National Weather Service (NWS)

The National Weather Service's Alaska Sea Ice Program (ASIP) is designed to service customers and partners operating and planning operations within and around Alaska waters. The Alaska Sea Ice Program offers daily sea ice (concentration and stage) analysis as well as sea surface temperature products. The ASIP has had a great need for a sea ice model that applies both atmospheric and marine influences to growing, moving, and melting sea ice and has been working closely with the developers of the RASM ESRL model during the 2017-2018 winter. A joint verification project between the RASM ESRL developers and the Arctic Testbed and Proving Ground (ATPG) has already shown promising results and has led to model improvements. In addition, the ATPG has been exploring general global atmospheric model variability during important freeze and thaw events and possible implications for Sea Ice modeling.

The stability of ice bridges using the Maxwell Elasto Brittle model

Mathieu Plante, **McGill University**

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

SIDFEx: The Sea Ice Drift Forecast Experiment

Axel Schweiger, **University of Washington**

TBD

The Formation of Double-Diffusive Layers in a Weakly-Turbulent Environment

Nicole Shibley, **Yale University**

Double-diffusive stratification in the ocean is characterized by staircase structures consisting of mixed layers separated by high-gradient interfaces in temperature and salinity. These double-diffusive layers, which can transfer heat vertically towards sea ice, have been found over a vast region of the Arctic Basin. Several past studies have examined the formation and thicknesses of these layers. In one formalism, the mixed-layer thickness is set by layer formation that arises when a heat source is applied at the base of water that is stably-stratified in salinity. We extend this work to consider the effect of turbulence on double-diffusive layer formation. We find that increased diffusivity ratios (ratios of salinity diffusivity to thermal diffusivity) result in thicker initial steps that take longer times to form. While this might suggest that larger mixed layer temperatures would occur at larger diffusivity ratios, in fact, larger diffusivity ratios may lead to decreased heat fluxes across interfaces. These reduced heat fluxes are due to increased transfer of salinity across the diffusive core, leading to interface growth. Moreover, layers decrease in thickness with height in the staircase, a function of the decreasing heat flux into a layer with height. The study has implications for the weakly turbulent Arctic Ocean where double-diffusive staircases are widely present and mixed-layer thicknesses are well-resolved by ocean measurements.

Skillful seasonal forecasts of Arctic sea ice retreat and advance dates in a dynamical forecast system

Michael Sigmond, **Environment and Climate Change Canada (ECCC)**

The need for skillful seasonal forecasts of Arctic sea ice is rapidly increasing. Technology to perform such forecasts with coupled atmosphere-ocean-sea ice systems has only recently become available, with previous skill evaluations mainly limited to area-integrated quantities. Here we show, based on a large set of retrospective ensemble model forecasts, that a dynamical forecast system produces skillful seasonal forecasts of local dates at which ice forms (the advance date) and melts (the retreat date) - variables that are of great interest to a wide range of end-users. Advance dates can generally be skillfully predicted at longer lead times (~5 months on average) than retreat dates (~3 months). The skill of retreat date forecasts mainly stems from persistence of initial sea ice anomalies, whereas advance date forecasts benefit from longer timescale and more predictable variability in ocean temperatures. Initial steps taken and challenges encountered in translating these results into operational products will be described. These results suggest that further investments in the development of dynamical seasonal forecast systems may result in significant socio-economic benefits.

The Impact of Stratospheric Circulation Extremes on Minimum Arctic Sea Ice Extent

Karen Smith, **University of Toronto Scarborough**

Given the rapidly changing Arctic climate, there is an urgent need for improved seasonal predictions of Arctic sea ice. Yet, Arctic sea ice prediction is inherently complex. Among other factors, wintertime atmospheric circulation has been shown to be predictive of summertime Arctic sea ice extent. Specifically, many studies have shown that the interannual variability of summertime Arctic sea ice extent (SIE) is anti-correlated with the leading mode of extratropical atmospheric variability, the Arctic Oscillation (AO), in the preceding winter. Given this relationship, the potential predictive role of stratospheric circulation extremes and stratosphere-troposphere coupling in linking the AO and Arctic SIE variability is examined. It is shown that extremes in the stratospheric circulation during the winter season, namely stratospheric sudden warming (SSW) and strong polar vortex (SPV) events, are associated with significant anomalies in sea ice concentration in the Barents Sea in spring and along the Eurasian coastline in summer in both observations and a fully-coupled, stratosphere-resolving general circulation model. Consistent with previous work on the AO, it is shown that SSWs, which are followed by the negative phase of the AO at the surface, result in positive sea ice anomalies, whereas SPVs, which are followed by the positive phase of the AO at the surface, result in negative sea ice anomalies, although the mechanisms in the Barents Sea and along the Eurasian coastline are different. The analysis suggests that the presence or absence of stratospheric circulation extremes in winter may play a non-trivial role in determining total September Arctic SIE when combined with other factors.

Canadian Contributions to the Year of Polar Prediction: Deterministic and Ensemble Coupled Atmosphere-Ice-Ocean Forecasts

***Gregory Smith,* Environment and Climate Change Canada (ECCC)**

The Year of Polar Prediction (YOPP) is running from mid-2017 to mid-2019 as the core phase of the ten year (2013-2022) Polar Prediction Project (PPP), an initiative of the WMO‘s World Weather Research Programme (WWRP), to enable a significant improvement in environmental prediction capabilities for the Polar Regions and beyond. As a Canadian contribution to YOPP, a number of deterministic and ensemble coupled environmental prediction systems have been running experimentally at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP). These include high-resolution short-range pan-Arctic coupled atmosphere-ice-ocean forecasts, global coupled medium-range forecasts and monthly ensemble forecasts.

The pan-Arctic coupled atmosphere-ice-ocean model has been developed to investigate the impact of coupled interactions in daily 48h forecasts produced in real-time during YOPP. The atmospheric component, the Canadian Arctic Prediction System (CAPS), runs over a regional domain with a 3 km grid spacing and has the latest innovations from the Global Environmental Multiscale (GEM) model, including a new Prediction Particle Properties (P3) microphysics scheme (clouds, precipitation). During the forecast, the atmospheric model is coupled at each time step to an ice-ocean model running over a regional 3-8 km resolution domain, covering the Arctic and North Atlantic regions, namely the Regional Ice-Ocean Prediction System (RIOPS). RIOPS uses the NEMO-CICE ice-ocean model and includes explicit tides, a landfast ice parametrization based on the effect of grounded ice ridges, and an increased resistance to tension and shear in the ice rheology (for improved representation in land-locked areas).

Additionally, a 32-day ensemble ice-ocean forecasting system has been running weekly since summer 2016. The potential usefulness of this system to provide guidance for long-range forecasts produced by the Canadian Ice Service has been investigated. Results of a subjective evaluation by forecasters at CIS and interactions with users in the Marine Shipping Industry will be presented.

Arctic sea ice extents, areas, and trends, revisited

Muyin Wang, **University of Washington**

More than 20 years ago, Parkinson et al. studied the Arctic sea ice extents, areas, and trends for the period of 1978-1996 based on satellite passive-microwave data. They found seasonal, regional, and interannual variabilities, with an overall decreasing trend in Arctic sea ice extents. Sea ice extent is widely studied and referenced, and climate models are often evaluated based on their sea ice extent simulations. Over the past decade, however, the condition has changed, especially with losing the thicker, multi-year sea ice in the Arctic. It is therefore necessary to revisit these variables. We will exam the sea ice extent, area, and the mean concentration in the Arctic based on two data sets: the HadISST_ice and Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 1.

A new Sea Ice Prediction Portal: year-round S2S sea ice forecasting

Nic Wayand, **University of Washington**

The recent declining extent and increasing variability of Arctic sea ice poses a unique challenge for S2S prediction. At the same time, there is an increasing demand for skillful regional sea ice forecasts due to the opening of Arctic waters. A significant barrier to understanding current model skill and targeting improvements is a lack of a central database to enable inter-model comparisons and evaluations. This study addresses this issue by extending the work started in 2008 that issues seasonal sea ice outlooks (SIOs) based on a diverse set of forecast techniques. Starting in 2018, and as part of the second generation of the Sea Ice Prediction Network (SIPN2), we have developed a central server and web portal housing multi-model ensemble sea ice reanalysis, reforecasts, and operational forecasts. Automated scripts re-grid and normalize diverse model forecast variables (sea ice concentration, ice thickness, snow depth, ice age, etc.) and evaluate historical reforecasts against available satellite observations. The portal also allows contributors to access formatted forecasts and perform their own analysis without the need to download large datasets. We will present an overview of the SIPN2 portal and provide examples of the type of analysis this database enables. Earlier results from the SIO found that shorter lead times (0-2 months) have the largest room for improvement predicting September minimum sea ice extent. We extend this work by evaluating multi-model ensemble reforecast skill for multiple sea ice variables at pan-Arctic and regional scale across the Arctic.

Estimating the sea-ice compressive strength (P*) from NASA IceBridge observations

James Williams, **NASA Goddard Institute for Space Studies (GISS)**

The surface winds in the Arctic Ocean largely force the sea ice towards the Canadian Arctic Archipelago (CAA). This has resulted in relatively thick sea ice in the region north of the CAA due to dynamic ridging. In the standard sea-ice strength parameterization, the slope of a sea-ice ridge depends on the ratio of the surface wind stress and the sea-ice compressive yield strength (P*). Using sea-ice thickness transects from NASA operation IceBridge, we are able to quantify the mean thickness gradient north of the CAA. This, along with observed surface wind fields, allows us to estimate the appropriate sea-ice yield strength for geophysical sea ice used in numerical models. Accurately calibrating the sea-ice compressive strength in numerical sea-ice model is of first order importance for accurately predicting sea-ice deformation, thickness and velocity.

Seamless prediction systems prove potential for skilful Arctic sea-ice forecasts far beyond weather time scales

Lorenzo Zampieri, **Alfred Wegener Institute,**

Helmotz Centre for Polar and Marine Research

With retreating sea ice and increasing human activities in the Arctic comes a growing need for reliable sea ice forecasts. Recently, the first operational forecasting centers started to integrate dynamical sea ice models into their forecasting systems, thus providing a new generation of "seamless" systems with the potential to boost our capabilities to predict sea ice weeks to months ahead. Here we assess for the first time the skill of these systems in predicting the location of the Arctic sea ice edge. We find that four out of the six systems are more skillful than a climatology-based benchmark for more than one week ahead. Averaged over the year, the best system provides skillful forecasts up to 1.5 months ahead; for late summer, when human activities in the Arctic peak, skillful predictions are possible even beyond 1.5 months. We argue that skill could be further extended through better initial conditions and more advanced forecast models. Our results highlight the fact that major improvements in the skill of long-term forecasts of Arctic sea ice are possible through investments in forecasting system development.