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Project Title:

Improved sea ice prediction through assimilation of ice thickness information and SAR image classification

Project Duration:

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Total budget request from MEOPAR: \$574,000



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Project Summary

Forecasts of sea ice information at high spatial resolution are expected to play a critical role in improving the safety of operations in ice-infested waters. For example, ice management around offshore structures and ship routing both require knowledge of ice concentration, thickness and drift. Providing this information at a high resolution is becoming urgent. Activities in the Canadian Arctic are increasing due to lighter ice conditions in response to warming temperatures, while becoming more hazardous due to more mobile and deformed ice. The lack of understanding and ability to forecast changing ice conditions poses a threat to these activities [1].

The majority of current sea ice forecasting systems assimilate data from passive microwave sensors, which have a spatial resolution of 5-50 km. Preliminary work assimilating higher resolution data from visual infrared (VIS/IR) sensors [2] and synthetic aperture radar (SAR) imagery [3] has been found to lead to improved representation of openings in the ice cover and details of the ice edge. However, these studies focused on ice concentration, and were not coupled to a sea ice forecast model.

The objective of the proposed research is to bring these data sources into an operational sea ice forecasting system, which will allow their impact on forecasts of ice concentration, ice thickness and ice drift, to be assessed. The work will contribute to building a bridge between those on the ice, who use SAR and VIS/IR for risk assessment [4], and those developing automated ice assessment and forecasting tools. This will be done through an interdisciplinary team, working along the following themes:

Ice thickness observations – will be obtained by airborne electro-magnetic (AEM) surveying to characterize ice conditions (thickness, ridging, and the occurrence of hazardous ice features [5,6]). The data will be used to develop relationships between SAR image features, and ice thickness and roughness, that can then be applied to imagery over wider geographic regions than can be sampled with aircraft. The airborne data will also be used for verification of automated image analysis algorithms, will be used in data assimilation, and will contribute to long-term, annual observations of ice conditions in the Beaufort region.

Automated image analysis – will be used to classify SAR imagery into ice/water and ice types using an established intelligent image analysis system [7-9]. Results will be verified with data from airborne surveys and assimilated in the data assimilation system.

Data assimilation – will be used to combine information from SAR and VIS/IR sensors with a background state from a sea ice model, and evolve this state forward in time. The emphasis will be on short-term (6 hour) forecasting at 2km resolution using the operational sea ice data assimilation system under development at Environment Canada.

Socio-economic potential impact of high-resolution ice forecasts from the data assimilation system will be assessed through surveys of shipping companies and analysis of shipping patterns. A ship route through the Beaufort Sea or Hudson Strait will be simulated, and the impact of improved ice information on the simulated route will be assessed.

Alignment with MEOPAR's Strategic Objectives

Northern Hazard Assessment

This project is directly aligned with the goal of evaluating marine hazards in the North. Sea ice is the defining feature of polar waters, and leads to substantially higher marine hazards compared to other waters. Through this project we will develop and begin an assessment of how sea ice forecasts may be used to facilitate safer and environmentally responsible offshore activities, and to guide economic and community development in the North. Through working directly with CIS we will support their mandate "At the Canadian Ice Service (CIS), our mission is to provide the most accurate and timely information about ice in Canada's navigable waters. We work to promote safe and efficient maritime operations and to help protect Canada's environment" (<http://www.ec.gc.ca/glaces-ice>).

Information and knowledge exchange

The proposed research represents a unique interdisciplinary collaboration between national and international experts in data assimilation, image processing, ice observations, and socio-economic implications of Arctic change. The proposed research will facilitate strong collaboration between all of these team members, and with external partners in government and industry. By working directly with the operational data assimilation system at Environment Canada (EC), knowledge developed at the university will directly impact products being disseminated to the public.

Fundamental Research

The proposed project will contribute fundamental knowledge on the interpretation and assimilation of observations from high-resolution sensors within a multivariate data assimilation system. Insight into the relationship between ice thickness and ice deformation will be gained by comparing ice thickness measurements with ice drift both in the observational study, and in the data assimilation experiments.

Private-Sector Participation

The proposed research involves Canatec Associates International Ltd, a company based in Calgary, AB, and Imperial Oil and Exxon Mobile. Canatec provides instruments, software and consulting services to oil and gas and shipping companies. Imperial Oil and Exxon Mobile own oil and gas leases in the Beaufort Sea and are leaders in offshore operations in ice covered waters and ice management. They are presently engaged in the acquisition of sea ice information in preparation of regulations and procedures for safe and environmentally responsible drilling and production in the Beaufort Sea, and were an active participant in the BREA (Beaufort Regional Environmental Assessment) project.

International co-operation

The Geophysical Institute of the University of Alaska Fairbanks (UAF) carries out numerous projects in the Beaufort and Chuckchi Seas regarding long-term observations and predictions of sea ice for various stakeholders including offshore oil and gas industry, coast guard, and local communities. They are strongly involved in the US Sea Ice Prediction Networks (SIPN). These activities will inform our planned Meopar activities. In turn, our results will benefit UAF research and will jointly contribute to better understanding and prediction of sea ice conditions in the Beaufort Sea.

An operational network

Investigating the use of high-resolution data in an operational sea ice forecasting system brings together ice observation studies and image analysis work, within the framework of data assimilation. This may strengthen and focus efforts put forth by various government agencies toward establishing an operational ice observation network, ultimately leading to safer and more efficient navigation and operations in the North. This project contributes to efforts being carried out by the Canadian Meteorological Center (CMC) and CIS to develop an operational sea ice forecasting system (the Regional Ice Prediction System, RIPS) that can be used both to support marine operations and for weather forecasting. The current project is complementary to the existing MEOPAR project 1.1 A Relocatable Coupled Atmosphere-Ocean Prediction System.

Project Description

Review of state-of-the-art

Accurate estimates of the sea ice state are critical for safe operations in ice-infested waters. In particular, improving estimates of sea ice thickness and drift are top priorities of both the operational and scientific sea ice communities. Ice thickness impacts the response of the ice cover to atmospheric and oceanic forcing, which manifests itself in ice drift and deformation. Highly deformed thick ice (e.g., rubble and hummock fields) is an obstacle and hazard to marine vessels and offshore structures. The deformation of thin ice can lead to increased openings in the ice pack, providing routes for shipping, and a source of concern for those traveling on the ice, or using it as a hunting platform. Ice-ocean models typically underestimate the thickness of the very thick and very thin ice [10], and do not show the observed trend of slower ice drift during months when the ice is thicker, and faster drift during the months when the ice is thinner [11].

Incorporating observational data into a model is an important way to improve forecasts. This can be done using data assimilation, a method in which observational data (e.g., in-situ observations from moorings, or satellite observations) is combined with a model state in an optimal manner. While the model provides a complete description of the sea ice state, including the ice concentration, ice thickness distribution, ice velocity and ice temperature, at every grid point as a function of time, the model state will drift away from the true state as it evolves forward in time. The objective in incorporating observational data is to produce an improved state estimate that can be used to re-initialize model forecasts. For an operational data assimilation system, observations are typically assimilated every six hours, meaning an improved state estimate is available four times each day.

Current operational sea ice data assimilation systems typically assimilate data from passive microwave sensors (5-55km), into models of resolution 10-30km [12]. New systems are being developed with model resolutions of 2 km to accommodate the need for higher resolution ice information. The assimilation of high-resolution ice information from SAR (50-100m) and VIS/IR (1km) sensors could make a significant improvement to these systems. Obtaining observational data from VIS/IR and SAR sensors suitable for assimilation is part of the challenge. For VIS/IR data, a thermodynamic model can be used to obtain ice thickness observations, with stringent quality control needed to eliminate cloud contamination [13]. For assimilation of SAR data, physical models are too complex, and empirical relationships are needed, e.g., between ice thickness measurements and SAR imagery. One of the most efficient means of obtaining ice thickness information coincident with and on similar scales as SAR image acquisition is AEM surveying. Challenges with obtaining relationships between AEM data and SAR imagery include, obtaining enough data for statistically meaningful results, and co-locating the SAR imagery with the AEM data [14].

Another way to use SAR data is through visual interpretation of the imagery, which is the method used by ice analysts to generate ice charts. The analysts use the visual tone and texture of the image, in combination with prior knowledge of the ice conditions, to identify regions where ice types at specific concentrations can be identified. These ice charts are currently assimilated in RIPS [15]. However, ice charts are only available at the times and locations that CIS has a mandate to provide them, and are time-consuming to produce.

Recent advances in computer vision have enabled some aspects of this type of image interpretation to be automated. For example, the MAGIC (MAp-Guided Ice Classification) [7-9] system, developed at the University of Waterloo, has the ability to classify a SAR scene on a per pixel basis. MAGIC includes a key published algorithm, IRGS that is able to robustly segment a digital image into regions that are homogeneous. However, as an unsupervised algorithm, IRGS only assigns arbitrary class labels (e.g., class A, class B, etc.) to each region and does not contain the information to assign true class labels (e.g., ice, open water, etc.). To determine whether a particular region has an ice or water label, a pixel-based

classification with true class labels is performed, resulting in an image where each pixel in the scene is labeled as either ice or open water. The algorithm has been tested on 60 dual-pol scenes with an overall accuracy of 95% [16]. An example is shown in Figure 1(b), with the original SAR image in Figure 1(a).

Assimilation of the ice/water information from MAGIC has been carried out through the first MEOPAR proposal [3], and results indicate improvements in the details of the ice edge. An example is shown in Figure 1(c). The proposed research will build on the discrete data assimilation methodology and image processing being carried out through the current Meopar proposal, while expanding the research team to investigate broader aspects of incorporating high resolution observations pertaining to ice cover and ice thickness, in an ice forecasting system.

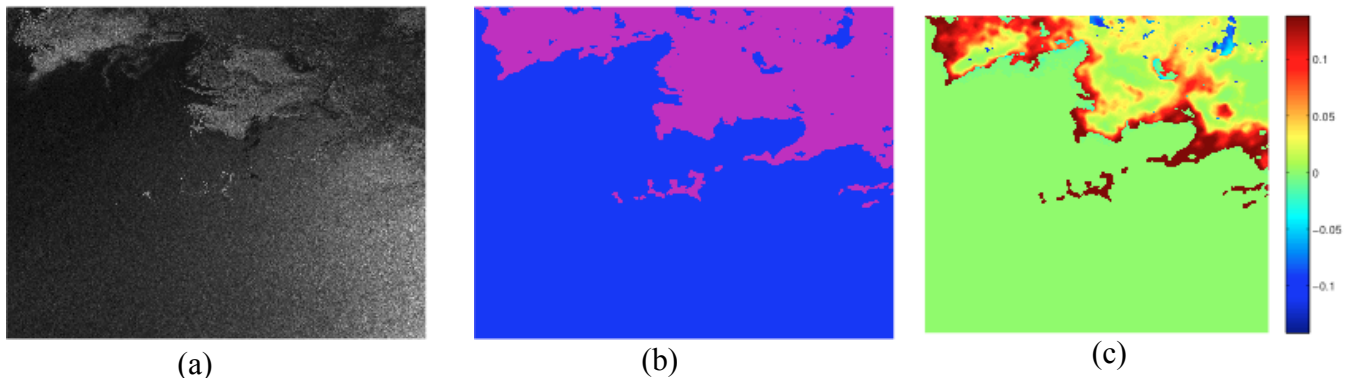


Fig 1: Original SAR image (a), ice (pink) water (blue) classification results (b) and analysis increment (c). The analysis increment is the amount of ice (%) added to the background state from the observations.

Research Approach

Ice thickness and drift observations.

Ice thickness measurements will be performed by means of airborne electromagnetic (AEM) sounding using a Basler BT-67 aircraft. AEM sounding is used to obtain the ice thickness and pressure ridge distribution along the flight track. Small- and large-scale ice thickness surveys will be carried out in April 2015 and 2016. These will provide ice thickness data for assimilation into the forecast model, for the development of SAR-derived ice thickness maps, and to quantify the regional distribution and thickness of multiyear ice and extreme ice features in the southern Beaufort Sea. To ensure proper co-registration of SAR imagery with the AEM data, in April of 2015 ice beacons will be air-dropped from the aircraft at the beginning of the AEM survey period. The beacons will each be equipped with a GPS sensor that will communicate the beacon position via satellite. This information will be used to correct for ice drift in the time between when the survey was carried out and when the image was acquired. The co-registered data will be used to develop relationships between SAR image features (e.g., backscatter, texture) and the AEM thickness measurements, taking into account the uncertainties in each. The beacon data will be compared with ice drift measurements calculated using SAR imagery using the Canadian Ice Service-Automated Sea Ice Tracking System (CIS-ASITS). For the second set of AEM surveys, in April 2016, drift from the ASITS system will be used in place of beacons to facilitate co-registration between SAR imagery and AEM data.

A scanning laser altimeter will be mounted to the aircraft to provide two-dimensional swath information of freeboard, surface roughness, and pressure ridges. Changes that will need to be made to the aircraft to accommodate the scanning altimeter will be made through an in-kind contribution (C. Haas). A vertically downward-looking camera will obtain overlapping photographs for visual interpretation and verification of satellite imagery. An overview of how the airborne data will be used can be found in Fig 2.

Imaging

The computer vision methods will build on the existing MAGIC image classification system, which is able to accurately classify SAR sea ice imagery into two classes, ice and water in an automated manner [16]. Further validation and development will be carried out to demonstrate the capabilities of the ice/water classification to support operational interests. The MAGIC system will be extended to ice type classification. This will further develop the capability of MAGIC to perform automatic classification for problems with more than two classes. Beyond solving the binary classification problem (ice and no ice), the objective is to perform ice typing by classifying homogeneous ice regimes into constituent classes (e.g., grey ice, multi-year ice, etc.). Techniques that are expected to have improved performance relative to the current model, namely random forests and rotational forests, will be investigated.

Data Assimilation

The data assimilation portion of the study will evaluate the assimilation of observations from VIS/IR and SAR sensors in a sea ice data assimilation system (RIPS [15]), which is based on 3D-variational data assimilation. In RIPS, the spatial structure of the background error covariance matrix is represented using a diffusion equation, and the system is capable of incorporating error correlations between different model variables (e.g., ice thickness and ice velocity). It is coupled with the CICE sea ice model, in which the role of the ocean is parameterized using a mixed layer model. This representation of the ocean is sufficient for ice forecasting when a 6-hour assimilation window is used.

To assimilate data from SAR sensors, relationships between co-registered SAR imagery and AEM data will be used to estimate ice thickness using a set of images from the Beaufort Sea. These estimates may be reliable over only a limited range of ice thickness. To complement this information, ice type (new ice, level ice, deformed first-year ice, multi-year ice) derived from the SAR imagery using the image analysis system, MAGIC, will also be assimilated using a novel mapping from the state space (ice thickness) to the observation space (ice type). Information on the thickness of thin ice (less than 0.7m) calculated from VIS/IR infrared surface temperature [13] will be assimilated when available (cloud-free conditions). Ice and water observations will also be assimilated using methods established in the first Meopar project [3].

Results from assimilation studies will be compared with those from independent data sources. Focus will be on ice thickness (including pressure ridges), ice drift and ice concentration. To have a correct assessment of the impact of the observations in the data assimilation system, error correlations between state variables (e.g., ice thickness and ice velocity) must be taken into account. This will be done in consultation with the data assimilation team at EC. Before the observations can be assimilated it will be necessary to develop quality control criteria to remove outliers [13], and may also be necessary to apply a bias-correction method. Assimilation studies will be carried using SAR images and VIS/IR data from the Beaufort Sea, and a region of the Canadian East Coast (e.g., Hudson Strait and the Gulf of St. Lawrence) using images provided from EC and from both the PI and co-PI's (D. Clausi) data sets.

Potential socio-economic and environmental benefits of improved ice information

Improved ice information will play an important role in shipping and in the supply of goods to local communities. As part of this project, an analysis of ship patterns (volume and spatial distribution) using a datasets from the Canadian Coast Guard and AIS data (that will be obtained in-kind from Transport Canada) will be conducted. This will be complimented with an analysis of sea ice conditions to determine the implications of sea ice variability on shipping patterns and trends, and a survey of ship operators about the potential value of improved ice information. A simulation will be carried out of a shipping route through the Beaufort Sea or Hudson Strait (to reflect increased use of the Northwest Passage and Arctic Bridge route respectively), and the impact of improved ice analysis on this route will be assessed.

Expected outcomes for the project

1. The airborne measurements will contribute to long-term annual observations of sea ice distribution

and change in the Beaufort Sea, as e.g. supported by the Beaufort Regional Environmental Assessment (BREA) in 2012 and 2013. Understanding long-term changes of ice conditions in the Beaufort Sea is key to being able to predict when shipping and offshore operations will become feasible in the region. They will allow assessment of hazardous ice conditions. These aspects have significant social and environmental impacts.

2. The capability of our MAGIC system to classify ice types in SAR imagery will be evaluated by means of airborne thickness and roughness measurements and photos of the ice surface.
3. Environment Canada’s operational sea ice forecasting system, (RIPS) [15], will be modified to assimilate ice thickness information from SAR data, and the impact of both this and the assimilation of VIS/IR data will be assessed. These will be the first experiments to assimilate high-resolution satellite data for sea ice forecasting.
4. Potential socio-economic impacts of improved ice information will be assessed, with emphasis on shipping patterns and safety.
5. The funding will contribute to interdisciplinary training of 5 HQP, allowing them to develop key skills and experience toward future work with companies and government agencies active in the Arctic.

Long-term outlook

The sea ice measurements will contribute to a growing database to support ice mass balance studies of the Arctic, and hazard assessment in the Beaufort Sea. Similar databases are developed and maintained by our collaborators at UAF. Establishing methods to use this data synergistically with that from satellites will contribute to long-term ice monitoring tools. This synergistic use comes from analysis, interpretation and assimilation of the available data. An important future study is the identification of regions in the Arctic that would most benefit from high-resolution ice forecasts. An analysis of the most used zones will be conducted to determine these regions.

Modifications made to RIPS and new image processing methods will enable optimal use of other sources of high-resolution data, such as SAR data from Sentinel 1 and the Radarsat Constellation mission. The development of methods to classify SAR imagery into multiple classes can be used in the future for detection of oil/ice/water, a high priority area by industry, governmental agencies and local communities.

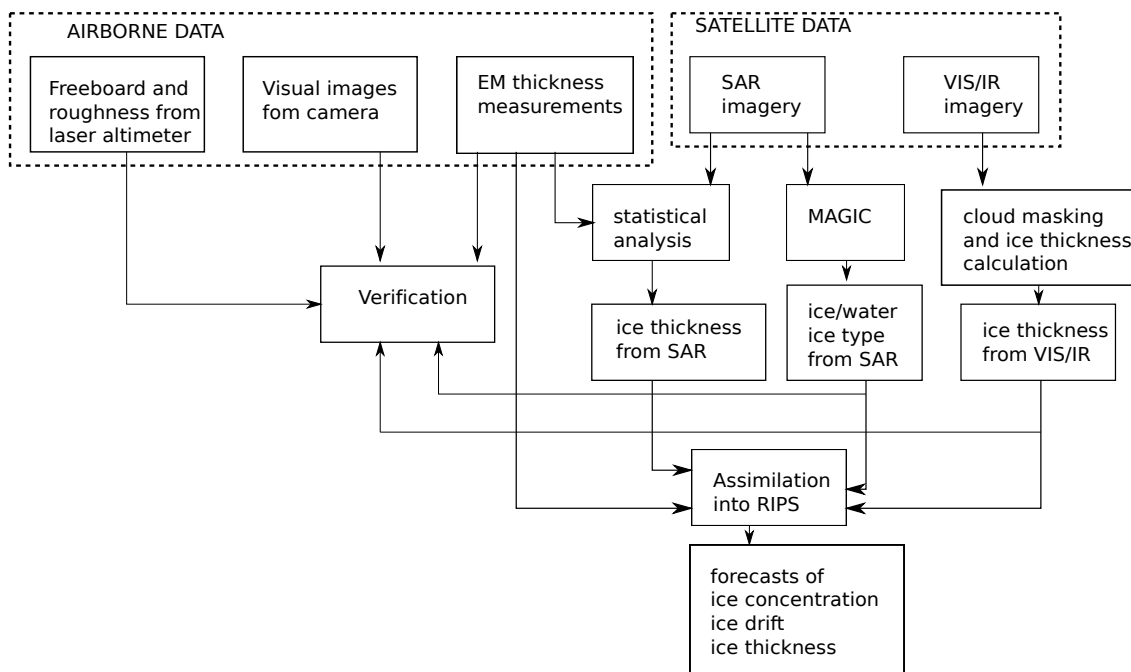


Fig 2. Flowchart indicating how the data and analysis tools will be used together.

Timeline

	2014-2015			2015-2016			2016-2017	
Measurements	F	W	S	F	W	S	F	W
1 Acquire airborne thickness (AEM) data and coincident SAR imagery			■			■		
2 Collocate AEM data and SAR imagery using either ice beacons or CIS tracker system				■			■	
3 Evaluate relationships between EM thickness and SAR image texture and/or backscatter				■	■		■	■
Image Analysis								
1 Development of semi-supervised methods to create ground truth of ice types using SAR imagery and by visual interpretation and CIS ice analyst validation	■							
2 Evaluate different methods for multi-class labeling of full SAR scenes and develop new algorithms	■	■	■	■	■	■		
3 Use AEM thickness data, camera images and airborne altimeter data, to assist full scene ice validation of new SAR scenes				■			■	
4 Evaluate new algorithms on validated SAR data.						■	■	■
Data Assimilation								
1 Develop model to assimilate ice type (discrete) data and test offline	■	■						
2 Students learn about RIPS system	■	■						
3 Modify RIPS to assimilate ice/water observations from SAR (using MAGIC) and verification using previous data sources and camera images		■	■	■	■			
4 Assess ice thickness forecasts from RIPS without thickness assimilation			■					
5 Modify RIPS to assimilate ice thickness and ice type data (from MAGIC and VIS/IR)		■	■	■				
6 Develop quality control (QC) criteria for ice thickness and ice type data from SAR and check previous QC used for ice thickness from VIS/IR		■	■	■	■			
7 Assimilate ice thickness/type data and verification			■	■	■	■	■	■
Socio-economic impacts								
1 Surveying ship operators about information requirements	■	■	■					
2 Analysis of shipping patterns and ice conditions in the Arctic	■	■	■	■				
3 Simulation of ship route planning through the Beaufort Sea in April and assessment of improved ice information on route safety				■	■	■		

Excellence and Interdisciplinary Balance of the Research Team

The research team is comprised of specialists in sea ice studies from a wide range of backgrounds, who are employed in a variety of sectors. Through this team we will have expertise in ice observation (both airborne measurements and satellite imagery), image processing, data assimilation and large-scale optimization, and socio-economic impacts of the changing ice cover. Through an interdisciplinary team we will be able to address the challenging problem of bringing high resolution satellite data into a sea ice forecasting system.

Andrea Scott (PI-Assistant Professor University of Waterloo – UW) specializes in the assimilation of passive microwave, AVHRR and SAR data to improve short-term forecasts of sea ice concentration and thickness. She is the PI for a MEOPAR project and for a Grant and Contribution project from Environment Canada. Prior to her appointment at the University of Waterloo she was a postdoctoral researcher in the Data Assimilation and Satellite Meteorology Research Section at Environment Canada. She is also a collaborator for the VITALS project regarding modeling and data assimilation in the Labrador Sea.

David Clausi (Professor, University of Waterloo - UW) specializes in the fields of Intelligent and Environmental Systems. Prof. Clausi is an active researcher with an extensive publication record of 50 refereed journal papers and over 70 refereed conference papers in diverse fields. His key research project is the automated interpretation of sea-ice in SAR imagery in support of Canadian Ice Service operations. He was the Co-chair of IAPR Technical Committee 7 – Remote Sensing during 2004-2006. He has received numerous scholarships, paper awards, and two Teaching Excellence Awards. As examples, he received the 2010 award for “Research Excellence and Service to the Research Community” by the Canadian Image Processing and Pattern Recognition Society (CIPPRS).

Christian Haas (Professor, York University - YU) is a Canada Research Chair in Arctic Sea Ice Geophysics and specializes in in-situ, airborne, and satellite observations of sea ice properties and processes. Dr. Haas has established operational airborne ice thickness surveys to obtain climate change information and in support of offshore marine operations. Dr. Haas was the Head of the Sea Ice Section of the German Alfred Wegener Institute for Polar and Marine Research, before moving to the University of Alberta in 2007 as the recipient of a highly endowed Alberta Ingenuity Scholarship. He moved to York University in 2012. Dr. Haas is a PI in the Beaufort Regional Environmental Assessment (BREA), in the NSERC CanSISE network, several Canadian Space Agency Radarsat SOAR (Science and Operations Applications Research) projects, and with the European Space Agency CryoSat validation project. He is also the Co-Chair of the International Arctic Buoy Program.

Claude Duguay (Professor, University of Waterloo - UW) specializes in remote sensing and in-situ observations and modeling of freshwater ice and sea ice, and Arctic climatology. He is author/co-author of over 190 publications and more than 375 presentations on related topics. Results from his research have appeared in many high profile international reports dealing with climate and the cryosphere, including IPCC 2007. He is past head of the Marine and Freshwater Ice Division, International Association of Cryospheric Sciences (2007-2011), past vice-president of the International Commission on Remote Sensing, International Association of Hydrological Sciences (2007-2011), and former member (2008-2012) of the Polar Distributed Active Archive Center User Working Group (PoDAG) of the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

Kumaraswamy Ponnambalam (Professor, University of Waterloo –UW) is a specialist in optimization of large systems. He currently works on ice thickness data assimilation and optimal path planning that can be used for shipping.

Jackie Dawson (Assistant Professor, University of Ottawa – UO) is a Canada Research Chair in Environment, Society, and Policy and specializes at the interface of natural and social sciences. She is the PI on several SSHRC, government, and industry funded studies of the socio-economic impacts of environmental and economic change in Arctic Canada and Svalbard, Norway. She focuses on climate change, sea ice change, shipping, marine governance, and local implications of economic development.

Hajo Eicken (Professor, University of Alaska Fairbanks -UAF) specializes in micro-scale and regional sea ice properties and processes. He also investigates different uses of sea ice by indigenous communities, the private sector and the public at large to help decision-makers adapt to a changing Arctic. Dr. Eicken is the lead PI of the NSF supported Seasonal Ice Zone Observing (SIZONET) and co-PI of the Sea Ice Prediction Networks (SIPN). He is the SSG Chair of the US Study of Environmental Arctic Change program (SEARCH), which also oversees the US Arctic Observing Network, an important potential partner of Meopar.

Mark Buehner (Research Scientist, Canadian Meteorological Center - CMC) specializes in data assimilation for both atmospheric and sea-ice applications. He is the scientific lead for the development of sea-ice data assimilation systems at Environment Canada as part of the CONCEPTS and METAREAS operational forecasting systems. He is also internationally recognized for his research in variational data assimilation for numerical weather prediction. M. Buehner is currently a Research Scientist at Environment Canada in the Data Assimilation and Satellite Meteorology Research Section.

Tom Carrieres (Ice Modelling Manager, Canadian Ice Service – CIS) has extensive experience in sea ice modelling and operations, having worked at the Canadian Ice Service since 1986 in a variety of roles. He leads a team of physical scientists involved in: sea ice modelling and data assimilation; iceberg drift and deterioration models; and extended range ice forecast models. He has managed a variety of externally funded ice modelling research projects over the past 15 years, averaging about \$1 M/year

Matt Arkett (Acting Remote Sensing Manager, Canadian Ice Service) is responsible for providing technical, analytical and/or strategic advice on remote sensing issues related to CIS operations, and has extensive experience in the analysis of SAR data.

Neil Darlow (Senior Technical Consultant for Imperial Oil Geoscience and ExxonMobil Geophysics) is an Environment and Regulatory advisor with Imperial Oil in Calgary. For the past three years he has held the position of Environment and Socio-Economic Impact Assessment coordinator for the Beaufort Sea Exploration drilling program. In this role he oversees field data collection programs with academia, Inuvialuit traditional knowledge holders, industry colleagues and government departments to generate both scientific and traditional knowledge and to use that information to help design a safe and environmentally responsible drilling program in the Canadian Arctic. An important part of his role is in consulting with Inuvialuit communities in the Beaufort Sea Region to ensure that the views, opinions and concerns of the Inuvialuit are addressed as the exploration program advances. He will represent an end user group and provide guidance regarding the most valuable outputs from our project.

Multi-Sectoral Structure and Support

Linkages to other projects

The proposed research will build directly on current and past research projects carried out by the PI and Co-PIs. Currently, the PI leads the MEOPAR project “Improved Sea Ice Forecasts Through Classification and Assimilation of SAR Imagery”, which involves the development of methods to assimilate ice/water data from an image classification system, and automated classification of SAR imagery into ice types.

Linkages to other projects currently led by the PI include

- Grant and Contribution with the Sea Ice Data Assimilation Research Team at Environment Canada, which involves the development of methods to assimilate SAR imagery to support operational sea ice forecasting (in progress).
- NSERC Discovery Grant, entitled “Toward improved forecasts of sea ice thickness” (in progress)
- NSERC Climate Change and Atmospheric Research Project entitled (VITALS - Ventilation Interaction Transports Across the Labrador Sea) for which the PI is working on modeling and data assimilation using a coupled ice-ocean system (in progress)
- Fed-Dev project on the development of a method to assimilate ice thickness from passive microwave data and preliminary work on a method to route ships through ice infested waters (co-PI K. Ponnambalam - completed)

The planned research is complementary to Dr. Haas’ research program entitled “Canadian Sea Ice Mass Balance Observatory” (CASIMBO) supported by his CRC and NSERC DG grants. That research is focused on the high Arctic between Canada and the North Pole, which is a critical region to understand Arctic-wide sea ice changes because it is located downstream of the Transpolar Drift. Inclusion of the Beaufort Sea through this Meopar project is thus adding an important region of the Arctic, which is linked to CASIMBO’s main study region through the Beaufort Gyre. Dr. Haas recently completed a Beaufort Regional Environmental Assessment (BREA) project, entitled “Distribution and thickness of different sea ice types and extreme ice features in the Beaufort Sea”, which provided information on sea ice thickness and extreme ice features (EIFs) using airborne electromagnetic surveys and drift beacons in the Beaufort Sea. The proposed research will contribute to continuing observations of sea ice changes in this region. Airborne ice thickness measurements will utilize instrumentation developed with the support of Canadian Foundation of Innovation (CFI) funds.

CASIMBO also includes the acquisition and interpretation of SAR imagery from Radarsat, TerraSAR, and ALOS-2, and radar altimetry ice thickness measurements of CryoSat. The proposed project will benefit from and inform this area of research.

The research is complementary to Dr. Duguay’s NSERC funded Discovery Grant and Climate Change and Atmospheric Research (CCAR) Grant which involves the assimilation of remote sensing data for improved numerical weather forecasting at high latitudes.

The research is complementary to Dr. Clausi’s NSERC Discovery Grant on image processing, and funded project through the Ontario Centers of Excellence in co-operation with McDonald Detwiller and Associates on SAR sea ice imagery.

The project complements Dr. Dawson’s research on the human and policy dimensions of sea ice change and shipping patterns in Canada’s Arctic. This research is supported through her CRC (Canada Research

Chair), SSHRC Insight, and NEXTAW (Network of Expertise on Transportation in Arctic Waters) grants. Specific projects involve examining the relationship between sea ice and shipping patterns, hazards, and risks, better understanding the influence of sea ice patterns on shipping patterns and environmental or human disasters, and identifying the socio-economic implications and potential governance and policy responses for a changing Arctic shipping environment.

External partnerships

This project will involve collaboration with the EC sea ice data assimilation team. Exchange of ideas and will take place through participation in monthly meetings (remotely) and 3-4/year on-site visits. Part of the funding from the G&C will be used to support students travelling to CMC and CIS for visits of duration 1-2 weeks. CIS will also order SAR imagery as close to the aircraft flight times as possible, and will provide additional imagery for data assimilation.

End-user involvement

The data assimilation system that will be used, RIPS, has been designed to include the two metareas (designated by the World Meteorological Organization) over the Arctic, comprising Canada's new contribution to the Global Marine Distress and Safety System. Assimilating high-resolution information into this system has the potential to lead to significant improvement in terms of emergency response and navigation. This is particularly urgent, as vessel volume in Arctic Canada has grown by more than 75% over the past decade, while changing ice conditions has made travel through the Arctic more dangerous [1]. Policy makers, stakeholders, and local residents are in agreement that "it is only a matter of time before we witness a major shipping accident in Arctic Canada" [17]. Improved ice information will not only reduce the risk of travel through the Arctic, but can also contribute to improved socio-economic conditions in isolated northern communities, which rely on bulk carriers and cargo vessels to bring supplies and goods, and on tourism vessels for seasonal income that supports traditional livelihoods and cultural traditions.

Operational needs in the interpretation of remote sensing imagery and applications of improved sea ice products will be discussed with Canatec Associates International Ltd and Imperial Oil. The results of this Meopar project will be of immediate importance to Imperial Oil as a potential component of their future met-ice-ocean observation system and ice forecasting and management activities. While directly benefiting from the results of this project, we will also consult with Imperial Oil in the final designing of observations and the forecasting system to be of most use for this stakeholder. Discussions between Imperial Oil and Inuvialuit communities in the Beaufort Sea Region will provide another mechanism by which the potential socio-economic impact of the ice forecasts can be realistically assessed.

HQP Training

It is anticipated that five HQP will be trained through the proposed research program.

- Postdoc (at York U) who will plan and conduct the AEM surveys and will work on the comparison between ice thickness data and SAR imagery
- PhD student (at U Waterloo) who will work on image processing
- PhD student (at U Waterloo) who will work on the assimilation of data from SAR sensors
- MASc student (at U Waterloo) to work on the assimilation of data from VIS/IR sensors.
- MASc (at U Ottawa) who will work on the socio-economic impact of improved sea ice forecasts

Student and postdocs who are funded through MEOPAR funding will have several unique opportunities above and beyond those available to regular NSERC-funded graduate students.

Two HQP (postdoc and PhD student) will be given the opportunity to participate in the proposed EM surveys in the Beaufort Sea region. This fieldwork will provide a unique, learning experience. In addition to the hands on aspects of acquiring ice thickness data, the students will be able to see sea ice in its various forms and variations with their own eyes, an important prerequisite to develop a better understanding of their study object. In addition they will gain an invaluable appreciation for life in the north and the challenges associated with operating in the harsh northern climate. These experiences will prove essential for good job perspectives in ice-related government or industry positions.

Students working on data assimilation will use the data assimilation system developed at Environment Canada, the Regional Ice Prediction System (RIPS), developed for operational sea ice forecasting. This system will be made available to both the PI and the students funded on this project through a remote access agreement. Students working on both data assimilation and image processing will be encouraged to spend part of their time on site, either at CMC in Dorval (for data assimilation) or CIS in Ottawa (for image processing). These trips will be for 1-2 weeks in length.

Students will be strongly encouraged to interact with others in the interdisciplinary MEOPAR network through the MEOPeers program. This will allow them to develop a broader perspective on their research, and begin to establish some of their own networks.

Students will be expected to participate in key meetings, such as that of the International Ice Chart Working Group Data assimilation, and conferences (IEEE Geoscience and Remote Sensing Conference, International Society of Offshore and Petroleum Engineers, Polar Shipping Summit) and to write papers that can be submitted to high quality peer-reviewed journals.

Students will be given the opportunity to work co-operatively and in an interdisciplinary manner to increase the breadth of their educational experience. For example, students in the field of computer vision often work with remote sensing data without any first hand experience as to the source of the data and its operational needs. In our project, these students will have direct exposure to the data sources and the processing of that data, while building a strong understanding of the operational needs, which will further lead to improved, more usable solutions that are operationally meaningful. Similarly, students working on data assimilation often do not have a clear idea of the errors in the observational data they are assimilating, or a real appreciation for how the results of the assimilation may be used. The combination of field work, collaboration with EC, and work being carried out on socio-economic aspects of ice forecasts, will improve their perspective of this dimension.

Due to the geographic proximity of all PIs involved (mainly in southern Ontario) an annual meeting will

be held at the University of Waterloo. This will provide an opportunity for students from different universities to report on their progress, for the various collaborators to meet and discuss the status of their projects and their milestones for the coming year, and for feedback from the end-users. If the MEOPAR Partnership Workshop Program remains in place, we would like to couple one of these with a larger workshop with participation from a broader sample of interested parties, including those who may not currently be a part of a MEOPAR proposal. The shape and direction of the workshop is to be decided, but likely data sharing and end user requirements will be featured topics.

Students trained through the proposed research program will contribute to Canada's expertise in data assimilation, sea ice remote sensing and computer vision. Data assimilation is particularly under-represented within Canadian HQP training programs.

Budget Justification

Category	Year 1	Year 2	Year 3*	Totals
Airborne Thickness Surveys (aircraft charter)	175K	175K		350K
Ice drift beacons	20K			20K
Personnel				
1 Postdoc - measurements	48K	48K		96K
1 PhD student – image analysis	21K	21K	10.5K	52.5K
1 PhD student – assimilation of SAR data	21K	21K	10.5K	52.5K
1 MASc student – assimilation of VIS/IR data	16K	16K		32K
1 MASc student – social science	16K	16K		32K
Materials, Supplies and Dissemination	2K	5K	8K	15K
Travel (including field work)				
Field work (2 people – 1 CoPI+1HQP)	14K	14K		28K
Conferences and workshops				
ISOPE 2015 (1 HQP)	2K			2K
IEEE 2016 (1 HQP)		2K		2K
IICWG 2016 (2 HQP)		4K		4K
ASS or PSS (1 HQP/year)		2K		2K
MEOPAR workshops (5 HQP/once/year)	3K	3K	3K	9K
Annual team meeting at UW		5K	5K	10K
<u>Trips to EC</u>				
Training	5K			5K
Research trips (PI+1 or 2 HQP)	3K	3K	3K	9K
SAR imagery	50K	50K		100K
Totals	396K	385K	40K	821K
Partner funds from Dr. Haas' CRC operating budget for system integration and maintenance	60K	60K		120K
Partner funds from Dr. Scott's G&C with EC for student travel to EC for training	7K			7K
Partner funds from Dr. Scott's start up grant for student funding on data assimilation	10K	10K		20K
In-kind contribution from EC – SAR imagery	50K	50K		100K
MEOPAR funds requested	269K	265K	40K	574K**

* It is assumed that Year 3 is 6 months in length, from Fall 2016-March 2017.

** A reduced level of funding would be acceptable by the project team

Airborne thickness surveys

The requested funds will be used for two airborne campaigns of 8 days duration each in April 2015 (Year 1) and 2016 (Year 2). Surveys rely on the usage of a Basler BT67 aircraft owned and operated by Kenn Borek Air Ltd (KBAL) in Calgary AB. Only this aircraft is equipped with the provisions and certified to operate York's AEM system. Funds include positioning of the aircraft between Calgary AB and Inuvik NWT, as well as four-hour daily minimums required by KBAL, a common practice for aircraft charter. Funds also include the cost of fuel.

In April 2015 there is a possibility of participating in a German project that uses a Basler BT67 aircraft with a similar AEM system operated by the German Alfred Wegener Institute for Polar and Marine Research. Flights will be performed in Resolute Bay NU and Barrow Alaska. Although this project does not intend to operate in Inuvik, Meopar funds could be used to divert the aircraft to Inuvik for a few days

to perform one or two flights in support of Meopar. Charter of the German aircraft is almost twice as expensive as KBALs rates, however, there would be no costs for positioning the aircraft. Overall, costs could be reduced by almost \$75k with the Germans, but there would be fewer surveying days and hours, and less flexibility in aligning the flight tracks with SAR acquisitions.

Ice drift beacons

The requested funds are for four Calib parachute ice beacons, manufactured by MetOcean from Halifax, NS. These beacons can be deployed through a jump door at the back of a Basler BT67 aircraft during AEM surveys. These beacons will be deployed during the first AEM survey to track the ice when its position changes due to ice drift. They will thus mark the surveyed ice to be better identifiable in SAR imagery which may not exactly coincide with the times of AEM surveys due to orbit constraints and other operational limitations.

Personnel

Salary levels for HQP are representative of funding levels at the institutions where the student will be located and are similar to levels recommended by NSERC. A postdoc has been identified that already has excellent expertise in the area of proposed research (Alec Casey, PhD candidate at University of Alberta). The postdoc will be living in Toronto, hence the funding level has been selected to reflect the cost of living and experience of the postdoc.

Travel

Fieldwork travel includes travel to and staying in Inuvik, NWT, of 2 persons for a period of 10 days in April 2015 and 2016. Note that the cost of travel in the Arctic is higher than elsewhere in Canada

Funding has also been allocated for each HQP to travel international conference(s) or workshop(s). Example venues are as follows

- The IICWG-DA (International Ice Chart Working Group – Data Assimilation) workshop is small (40 participants), and informal and is a good place for students to present research and participate in round-table discussions with others working in the field. The 2014 IICWG workshop will be held in Toulouse (France) in September, and will be covered by the PIs current collaboration with EC. A date and location for the following IICWG workshop has not been announced, but it will likely be in northern Europe in 2016.
- IGARSS (IEEE Geoscience and Remote Sensing Symposium) and ISOPE (International Society of Offshore and Petroleum Engineers) involve submission of a paper for peer-review. These meetings will be held in Asia and Hawaii in 2015 and 2016, hence we may prefer to send only 1 HQP to each for budgetary reasons.
- ASF (Arctic Shipping Forum) and PSS (Polar Shipping Summit) are large meetings that can provide valuable presentation and networking opportunities to HQP.

Multiple students will be sent to the MEOPAR workshops. These are in Canada, hence the cost of travel is not as high/person. Students will also have opportunities to travel to CIS in Ottawa and CMC in Dorval to interact with the EC team. In the first year of the project 5K has been allocated to send two students for on-site training at EC. Funding has also been allocated for an annual workshop at UW, with the bulk going to support travel costs for international and national partners.

SAR imagery

An in-kind contribution of 20 SAR scenes will be provided by Environment Canada. Acquisition of these images will be carefully planned to coincide with the planned airborne surveys and beacon deployments. Additional scenes from the PI (K. Scott) and Co-PI (D. Clausi) covering Hudson Strait, and the east coast of Canada, will also be used.

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25 April 2014

Prof. A. Scott
Systems Design Engineering
University of Waterloo
Waterloo, Ontario N2L 3G1

Dear Prof. Scott,

Canatec Associates International Ltd. (Canatec) is a Calgary-based company specializing in ice consulting services to petroleum companies, shipping firms, polar researchers, and government regulators. Significant information is derived through the expert use of remote sensing satellite imagery to support these initiatives.

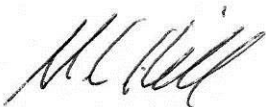
Canatec has interests in building systems for computer-aided interpretation of satellite data in general and of synthetic aperture radar (SAR) imagery in particular. The planned research involving the integration of data assimilation and computer vision systems is of interest to Canatec.

We are interested in providing operational requirements and personnel discussions to help shape the ongoing research prescribed in the MEOPAR proposal "Improved sea ice prediction through assimilation of ice thickness measurements and SAR image classification." We have an active interest in building automated scene interpretation systems for ice reconnaissance and feel that this project would be a good start that would parallel our in-house efforts. Also, we are willing to fund an employee to participate in a field mission with Dr. Haas to give them the hands-on experience necessary to further our R&D activities.

As part of our ongoing sea ice research in the Beaufort Sea, we are also very interested in the ~~operation of drifting GPS beacons, and would be glad to take advantage of deployment~~ opportunities during the planned airborne ice thickness surveys. We may consider providing and operating our own beacons, or providing them to the project for purchase at a discounted rate.

Basically, the project is an excellent fit to Canatec's interests. I hope that this information is sufficient to provide context to support this proposal.

Yours sincerely,
Canatec Associates International Ltd.



Chris Hill, President



Canadian Ice Service - Service canadien des glaces

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Andrea Scott
Assistant Professor
Department of Systems Design Engineering
University of Waterloo, Canada

2014-04-24

Re. MEOPAR proposal 'Improved sea ice prediction through assimilation of ice thickness information and SAR image classification'

Dear Andrea,

I have reviewed the subject proposal that you and your colleagues have submitted for MEOPAR funding. The work you propose meshes very well with the efforts of Environment Canada (EC) to develop the Regional Ice Prediction System (RIPS) – an automated sea ice analysis and forecast system. I also greatly appreciate your ongoing contributions to the EC sea ice data assimilation team. In terms of support for your project, I wish to highlight the following existing contributions that EC and the Canadian Ice Service (CIS) offer to our ongoing collaboration:

- We have requested that our Minister approve Grants and Contributions funding for your work in the amount of \$70k for FY 2014-15
- Through the G&C agreement, EC will also provide you with several frames of RADARSAT2 SAR imagery for your project. This imagery has a considerable cash value of approximately \$5000 per frame
- The EC sea ice data assimilation team will provide you with data from RIPS as well as routine feedback on your work through our monthly meetings and occasional workshops

As an in-kind but direct support to the current project, we plan to provide the following in addition to the above:

- EC will acquire and provide you with up to 20 frames of RADARSAT2 SAR imagery as nearly coincident to the EM sensor acquisitions planned for April 2015 and April 2016. This imagery has a cash value of approximately \$100k if ordered privately



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- The EC sea ice data assimilation team will provide you with access to RIPS for use in your project related sea ice data assimilation experiments
- EC will provide access to sea ice drift derived from RADARSAT SAR imagery using the EC ASITS system

In conclusion, on behalf of EC and CIS, I strongly support your proposal and wish you success in your application for MEOPAR funding.

Sincerely,

David Jackson,
Director, Canadian Ice Service



Imperial Oil Resources Ventures Limited
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Calgary, Alberta
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Neil Darlow
Beaufort Environmental Lead

Tel. (403) 237-4522
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April 24, 2014

Dr. Andrea Scott
Assistant Professor
Department of Systems Design Engineering
University of Waterloo, DWE 2501
200 University Ave West
Waterloo, Ontario
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Re: Letter of Support for "Improved sea ice prediction through assimilation of ice thickness information and SAR image classification" research program

Dear Dr. Scott,

I am happy to provide this letter of support for your current ice research program.

Imperial Oil is the operator of a Joint Venture examining the potential to drill one or more oil exploration wells in the offshore Canadian Beaufort Sea. Executing a safe and environmentally responsible exploration drilling program in the Beaufort Sea is complicated by the presence of ice conditions that vary both temporally and spatially. A key focus of our work is designing systems, processes, and operational plans to identify, assess, track and manage potentially hazardous ice. Understanding the temporal and spatial variability in ice thickness is an important component of this work. Taking direct measurements of ice thickness and using them to validate SAR-derived ice information and integrating that information into Environment Canada prediction models has the potential to broaden our ability to collect and use information on ice thickness, thereby improving the accuracy of our systems, and ultimately the safety and environmental performance of our exploration drilling program. As a potential user of the data from this research program, Imperial would be willing to engage the research team and to contribute to the design of the experiments, and to advise on the usefulness of the results.

Imperial is happy to have been able to support the ice research program in 2013 through our University Research Awards program, and was excited to meet recently with Dr. Christian Haas and his research team to see the results of that work. We look forward to exploring the potential for future support of the project.

Sincerely

A handwritten signature in blue ink, appearing to read "Neil Darlow".

Neil Darlow
Environmental Lead
Beaufort Sea Exploration Drilling Program
Imperial Oil

21 April 2014

Andrea Scott
Assistant Professor
Department of Systems Design Engineering
University of Waterloo, DWE 2501
Waterloo, Ontario
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Subj: Letter of Support, proposal on Improved sea ice prediction through assimilation of ice thickness information and SAR image classification

Dear Dr. Scott,

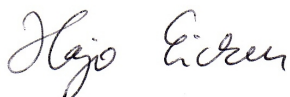
This letter is to indicate my strong support of your proposed research on “Improved sea ice prediction through assimilation of ice thickness information and SAR image classification” to the Marine Environmental Observation Prediction and Response Network (MEOPAR). Your proposal is timely and addresses an urgent need, both from the scientific and stakeholder/operator perspective, in improving sea ice prediction on short-time scales.

As a co-Investigator of the Sea Ice Prediction Network (SIPN), an activity of the U.S. Interagency Study of Environmental Change (SEARCH) which I currently chair, I am excited to see this work proposed as a potential contribution to SIPN. SIPN has made great strides in the past six months and one of the key gaps we have identified is in fact the very problem you are trying to address. The proposed work would thereby address key questions identified by our partners at the North American Ice Service as well as other stakeholders linked to the project.

At the same time, in my role as PI for the Seasonal Ice Zone Observing Network (SIZONet) the combination of enhanced remote sensing data analysis and airborne ice thickness surveys for assimilation into short-term ice forecasts is extremely compelling and represents an ideal complement to the SIZONet work we are conducting in northern Alaska. We plan to collaborate closely with you and your team to ensure full interoperability between the data sets collected by our respective teams. While all SIZONet datasets are publicly available soon after collection and quality control, we will make a special effort to fully share at the data processing stage to generate potentially seamless ice thickness survey data sets and related products. This may then also feed into the SIPN data library for model initialization and validation maintained at the National Snow and Ice Data Center.

Finally, the social/political science component of our work, led by my colleague Dr. Amy Lovecraft, may also be of interest to your team. Specifically, your work may lend itself for a comparative, cross-border analysis of the role institutions (rule sets, formal governance instruments, laws etc.) can play in guiding sea-ice predictions and related observation efforts.

With best wishes for the success of your compelling proposal,



Hajo Eicken
Professor of Geophysics
e-mail: hajo.eicken@gi.alaska.edu, phone: 907-474-7280; seaice.alaska.edu/gi