Proposal

Synopsis:

This project will advance physical oceanography by producing new knowledge about iceberg drift and develop software to be used by PAL for their commercial activity of providing iceberg management services. The principal beneficiaries of this software will be PAL and their clients including operators of offshore oil and gas exploration and production facilities on the east coast of Canada.

The overall goal of the project is to *improve operational iceberg drift predictions by measuring the uncertainty and developing an ensemble iceberg drift forecast model*.

Specific objectives to be completed over this four-year project are

1. Assess the uncertainty and error rate of current iceberg drift models using historical iceberg data.
2. Couple an iceberg drift model to modern ocean models to supply ocean current forcing.
3. Implement an ensemble iceberg drift model by comparing iceberg trajectories forced by ocean models as well as different wave and wind models.
4. Validate and measure uncertainty from ensemble models against historical iceberg data provided by PAL.
5. Work with PAL to implement this new ensemble iceberg drift model into their operations.

The proposed work will improve predictions of iceberg drift by characterizing the uncertainty using ensemble modeling and historical data analysis.

Background:

The prediction of iceberg motion is vital to the safety of both offshore oil installation and ships that travel the North Atlantic. Ice management is used to reduce down time for floating structures and to reduce the probability of impact with fixed structures. Ice management can also be accounted for in the design process of offshore oil and gas structures to reduce design loads and thereby to reduce the capital costs of offshore structures, while maintaining the appropriate levels of safety (Eik & Gudmestad 2010; Younan et al. 2012).

Improving the prediction of iceberg movement leads to less downtime, lower costs and lower risks for oil and gas operators and therefore higher tax, royalty, and regional benefits for Provincial and Federal governments. To improve the prediction of iceberg motion, we need to quantify the uncertainty in the forces acting on the icebergs.

Ocean currents, winds and waves contribute to the complicated dynamics of iceberg motion. Iceberg motion is presently forecasted using physics-based models that compute iceberg accelerations based on the forces acting on the iceberg (Eik 2009). But even for current state-of-the-art iceberg drift models, it is a challenge to predict the detailed path of an iceberg 12 to 48 hours into the future due to uncertainties in the estimates of the driving forces (Turnbull et al. 2015).

Any prediction has a certain degree of uncertainty and for a prediction to be useful we need to be able to quantify that uncertainty. Ensemble forecast models are able to incorporate the variations of several different ocean models to give a range of uncertainties associated with better iceberg drift predictions. Simple ensemble modeling for iceberg drift prediction by varying environmental parameters and iceberg properties (Allison et al. 2014) using a Monte Carlo approach have been investigated previously. This project will be different from previous studies because it will integrate multiple ocean current, wind, and wave forecast models as ensemble members and will verify the predictions with the largest database of empirical data on the subject. This new model will be validated using extensive historical datasets on iceberg trajectories provided by Provincial Aerospace Ltd. (PAL) a collaborative partner on this research.

Iceberg drift modelling has been an area of active research (Turnbull et al. 2015; Wesche & Dierking 2016). Even so, current iceberg trajectory models used by PAL do not give specific information to operators about the uncertainty associated with the prediction. Moreover, different iceberg models make different predictions about the short term path predicted for specific icebergs. Ensemble modelling as proposed here is a way forward to improve iceberg drift forecasting.

Detailed proposal:

The project is planned to be completed over four-years by accomplishing the five major activities as described below. The plan is structured around four graduate students (two masters and two doctoral students) pursuing thesis-level research under Dr. Munroe's supervision with regular participation from PAL.

1. Simple Iceberg Drift Model ***20 months, 2017-01-01 – 2018-08-31***

An initial activity for this project will be the implementation of a command-line based simple iceberg drift prediction model. This new software will serve as a basis for the development of the enhanced ensemble iceberg drift model. It will also serve as a research and development platform for the overall project. The software will be developed based on the physics-based models available in the peer reviewed literature (Kubat et al. 2005; Turnbull et al. 2015). This new implementation will have abstract interfaces for ocean model data and other forcing input from arbitrary data source providers. The development and implementation of this iceberg drift model will be the initial activity **PhD1**.

This tool will numerically integrate the trajectory of an iceberg and store the results in an external file format. The details of the software design will be developed in early stages of the activity. It is anticipated that the model will be developed in Python. The software ecosystem for Python is quite mature and there are several open-source libraries that may integrated into this new software. As input, the program will require an initial position of an iceberg, parameters about its shape and size, and time series information including forecasted wind, waves, and currents for the region around the iceberg. As output, the program will produce a time series of projected positions for the iceberg. This model will focus the short term (12-48 hour) trajectory of the iceberg.

The input and output formats for data will be developed in consultation with PAL. The data formats supported will include at least CSV and NetCDF4 in addition to other industry standard formats. PAL will offer guidance on integration with their existing software.

The model itself is not expected to be computational expensive since it is fundamentally integrating an ordinary differential equation. However, if needed, portions of the model will be rewritten in C or another compiled language. This is a common methodology when developing in Python.

As the simple iceberg drift model will be used for research as well as operational purposes, the software will be instrumented with the ability to measure and monitor the details of the model. These additional services, which could be disabled in an operational version of the code, will be essential for determining the relative importance of the different forcing parameters.

This software will be developed using best practices from software development. In particular, a test suite will be implemented to verify the components of the code and the software overall works as intended. The activity includes the writing of documentation for both end users and future developers. The software developed detailed in the other activities will adhere to the same best-practises.

2. Historical Iceberg Data Assessment ***24 months, 2017-01-01 – 2018-12-31***

Every year, there are several hundred icebergs in the North Atlantic. Over the past 3 decades PAL, through its aerial surveys, identifies and tracks those icebergs and has amassed one of the largest databases of ice data in the world. PAL uses conventional iceberg drift models to predict the trajectory of each iceberg into the future and verifies their shape, size, position, and track.

This historical assessment will investigate the success rate of iceberg drift prediction to serve as a baseline for further improvement. Also, criteria that are associated with poor iceberg drift predictions will be determined. For this project, PAL will set up and support access to their dataset of iceberg observations that can be used to assess the uncertainty and variability associated with iceberg drift prediction. Machine learning will be used to identify icebergs and ocean conditions that typically lead to poor accuracy in predictions. This information will be used to develop the new model that targets those sources of uncertainty. This activity will be performed by **MSc1**.

3. Operational Ocean Model Forcing ***28 months, 2017-01 – 2019-04-30***

Numerical ocean models have continued to improve and should be used in iceberg drift prediction models. For example, the Canadian Operational Network of Coupled Environmental Prediction Systems (CONCEPTS) project, pursued jointly between the Departments of Environment Canada and Climate Change, Fisheries and Oceans, and National Defence, developed the Global Ice-Ocean Prediction System (GIOPS) model which is specially aimed at the North Atlantic region (Pellerin et al. 2015; Dupont et al. 2015). This data assimilating ocean model in turn was based on the Nucleus for European Modelling of the Ocean (NEMO) ocean model coupled with the Los Alamos Sea Ice Model (CICE). Another example of a state-of-the-art data assimilation model is the independently developed Global Real-Time Ocean Forecast System (RTOFS) which is built upon the Hybrid Coordinates Ocean Model (HYCOM) (Metzger et al. 2014; Mehra & Rivin 2010). This second model was developed, in part, for the operational needs of the US Navy.

Models like GIOPS and RTOFS provide operational forecasts of ocean conditions at high spatial and temporal resolutions of the North Atlantic. Ensemble forecast models are able to incorporate the variations of several different ocean models to give a range of uncertainties associated with iceberg drift predictions. For the current project, we need to provide input to the iceberg drift model. Other operational ocean models (Dombrowsky 2011) and other models including wind and wave models to be determined may also be considered. The task of working with this operational oceanographic model output will be the primary activity of **PhD2**.

While the output formats of each individual ocean, wind, or wave operational model is standardized, it is anticipated that there will be work needed to convert, transform, rescale, and/or translate from the output data formats into a data format suitable for input to the iceberg drift model. The software development and testing of these conversion tools are part of this activity. Since the model output needs to be processed in a timely manner, attention will be given to ensuring that there are no computational or data transfer bottlenecks in importing and preprocessing the data from these external sources.

Operational ocean models produce a significant amount of high resolution data. Some of this data is not publically archived since it no longer serves an immediate operational benefit. This project will archive locally (either through external storage or cloud-based storage) the results of these operational models. Simply archiving these models produce will likely exceed available disk space. Most of the data may not be useful to this project since it describes regions far away from where iceberg typically travel. This activity will determine and justify which components of ocean, wind, and wave models need to be archived for verification and validation of the ensemble iceberg drift model.

4. Ensemble Iceberg Drift Model ***24 months, 2018-05-01 – 2019-04-30***

The new iceberg drift model will be run against multiple ocean model data sources and with variations of the physics based parameterizations. This will produce an ensemble iceberg drift model. This code is intended for eventual use by PAL in their ongoing operations. This activity will be heavily influenced by the progress and outcome of activities 2 and 3. This major activity will require participation from both **PhD1** and **PhD2** along with regular collaboration with ice management specialists from PAL.

This software development activity will create the actual model which is the goal of this project. The code will extend the simple iceberg drift model from activity 1 by running many parallel instances of the simple model which will each constitute a member of the ensemble. Each model will have input from different physical parameters and ocean model input. The physical parameters will be drawn from probability distributions that capture the uncertainty of the underlying parameter. The use of several ocean models will minimize the biases of any one operational model. Initially, ensembles will be simple averages of the member iceberg drift model runs with the incorporation of historical data from PAL's iceberg data network (specifically through activities 2 and 5) weighted averages that assess the relative confidence of the different operational model input. The determination of the optimal weights between members of the ensemble will be determined through a machine learning model based on the historical data.

Since this software is intended to be operationally used by ice management specialists at PAL, their involvement throughout the activity is crucial. The model will eventually need to be integrated with PAL's Ice Data Network System by their Software Engineering Division. The user interface and visualizations developed for the ensemble model will need to work with PAL's overall workflow in their ice management group.

The objective of the activity is a beta software version that will be usable by PAL in their operations. The ensemble model will be divided into a command line interface (CLI) back-end and web-browser based interface (BUI) front-end. The back-end will be run on a Linux computer which will persistently store its model output. This code will be structured like a software service with automated components for both importing of new external data sources and running the simple iceberg models which will serve as members for the ensemble.

The front-end will run on any platform (Windows, Mac, or Linux) with a modern web-browser. This platform independence is major advantage of a BUI over a desktop based graphical user interfaces (GUIs). There are many possible frameworks for BUIs available typically using a combination of JavaScript, HTML, and CSS. The separation of the model between a back-end and front-end allows for the user interface to change depending on the eventual end-user. In the beta version of this research-grade software, the user interface and user experience will attempt to show a significant amount of diagnostic and status information

A critical visualization element will be the presentation of the ensemble model prediction of the expected iceberg path. The visualization will need to show the uncertainty associated with the forecasted trajectory. One method of accomplishing this is to project a fan or cone shape onto a geographical map of the region with the iceberg. The visualization will show the most likely path as function of time along with colour-coded confidence intervals to describe the possible variability in the trajectory.

5. Validation of Ensemble Model Against Historical Data ***24 months, 2019-01-01 – 2019-12-31***

The ensemble iceberg drift model will need to be validated against historical iceberg observations and new iceberg motion data provided by PAL during the project. Although this task will involve contributions from both PhD1 and PhD2, this validation will be the primary activity of **MSc2**.

The iceberg sightings database will continue to grow as observations are collected by PAL. This historical record, along with archived results of ocean, wind, and wave model output especially over the four-year duration of the project, will serve as a test dataset to both validate and measure the uncertainty of the new ensemble model developed in future activities. Software tools and workflows will be developed to automate this validation step so that it can be reproduced as further improvements to the model are made

This activity will include a technical report made available to PAL that identifies the strengths and weaknesses of the new ensemble model. The objective of this activity is to provide measurable information on the operational usefulness of the model. It also will suggest areas for further improvement and development.

As principal investigator, Dr. James Munroe will contribute actively to all five of these activities. One local student has already been identified (Evan Kielley, student **MSc1**) the other graduate students need to be recruited and relocate to St. John's, NL. While preliminary work on activities 1, 2, and 3 will begin as soon as possible, the expectation is the students will spend a significant amount of time in their first year completing required coursework, learning skills in high-performance computing, and reviewing the existing literature.

This research team anticipates completing the following deliverables for operational use by the industrial partner, PAL, by the end of the project, 2020-12-31:

1. Command line based software and associated source code for predicting the position of an iceberg 24-48 hours after an initial observation. The model will require appropriate operational met-ocean model input. Data formats for input and output of data are to be developed in consultation with PAL.
2. Research and development of a new ensemble iceberg drift model that provides information on the uncertainty of the iceberg trajectory prediction. This model will be implemented and delivered as research level software that will require future software development to be fully integrated into PAL's ice management operations.
3. Validation and verification of the performance of the ensemble iceberg model using PAL database of historical and current season iceberg observations. The results of this portion of the research will be communicated to PAL executives and in scientific peer-review research papers and in technical reports.

Research questions concurrent with the development of the software deliverables to PAL will also be pursued by Dr. Munroe and his team in the context of understanding the uncertainty associated with different components of the iceberg drift model. As examples, the importance of iceberg geometry, the impact of internal waves, and the role of oceanic eddies on iceberg drift are possible research directions to be investigated with this new iceberg drift model and PAL's historical dataset. While it is difficult to anticipate the timelines on these research questions, such advances in physical oceanography discoveries, related to iceberg drift prediction, will be reported in the peer-reviewed literature both during and after this collaborative research project. Some of these potential research questions may pave the way for future research collaborations.

Team expertise:

Dr. James Munroe primary research areas are internal waves, stratified fluids, and fluid dynamic lab experiments. He completed his PhD at the University of Alberta in 2009 and then performed postdoctoral research at the Ecole Normale Superieure de Lyon. In 2010, he was appointed an assistant professor at Memorial University and teaches in the areas of physics, physical oceanography, and scientific computing. He established a Stratified Fluid Dynamics Laboratory that has so far graduated two MSc students. He recently received academic tenure and will promoted to associated professor in Fall 2016. Dr. Munroe's publications include papers on internal wave generation, wave instabilities, and autonomous underwater vehicle hydrodynamics.

Dr. Munroe's broader research expertise is in applied mathematics, physical oceanography, and data science. He has previous experience working with numerical ocean models and big data. His university teaching is on the topics of physics and mechanics, geophysical fluid dynamics, and scientific computing. This combination of skills and expertise is both sufficient and necessary to complete the project objectives.

Dr. Munroe is planning on taking a sabbatical year in 2017. During this period, he intends to continue to be fully committed to working on this project as a major component of his overall research program. During the early period of the project, the students will be completing their required graduate courses.

PAL is a world-class ice management company with extensive experience in providing iceberg observations and forecasts. In addition to providing access to their data, specialists from PAL are essential to this project to provide guidance on the industrial relevance of the research and consulting on empirical results when compared to theoretical data. This collaboration with the ice management division of PAL will be coordinated through Stephen Green, Director of Research and Development, PAL and Michael Ollerhead, Research and Development Coordinator, PAL.

Research management:

Dr. James Munroe is the principal investigator for the project. Dr. Munroe will be responsible for overall project budgeting, planning, reporting, and executing the project work plan. He will be responsible for communication among collaborators and student researchers, and with PAL, NSERC, and RDC. Dr. Munroe will have final authority and responsibility for all project activities, availing of both the financial and administrative services with the Department of Physics and Physical Oceanography and Memorial University, ensuring adherence to university policies and practices.

Dr. Munroe has previously managed a RDC Ignite Grant (Internal Waves and Mixing, 2011-2013). The RDC project successfully trained two master's students and two undergraduate research assistants. Dr. Munroe was the investigator behind a major activity task on the Atlantic Innovation Fund supported Responsive AUV Localization and Mapping (REALM) project. The activity as part of REALM was to add a large external wing to an autonomous underwater vehicle and evaluate its performance in lab experiments and field trials. In addition to research grants, Dr. Munroe has over ten years of experience of being a chairperson, treasurer, and/or board member for several community-based organizations.

As project leader, Dr. Munroe will review work of student researchers and provide feedback and guidance on the scientific aspects of the project. Dr. Munroe will meet biweekly with the students on the project. The overall project team is comprised of the PI, the graduate students, Stephen Green (PAL, Director R&D), Michael Ollerhead (PAL, R&D Coordinator), and members of the ice management division. This team will meet quarterly to discuss research progress, technical challenges that may arise, and solutions. Thus, strong communication between Dr. Munroe's research group and PAL will be maintained throughout the project period. This project is not large enough to justify a separate project manager. In addition to regular meetings with PAL, annual reports will be produced as required by NSERC and RDC.

Training of highly qualified personnel:

On this four-year project, four graduate students (two masters and two doctoral) will have the opportunity to work with the industrial partner, have access to high performance computing resources, and be supported for conference travel. As part of the project team, the students will proactively participate in group planning meetings and contribute to scientific manuscripts honing written and communication skills. PAL has offered to host graduate students on their premises for a few months during the iceberg management season. This placement will put their academic research in context with the needs of industry and prepare them for jobs in the Environment services and Aerospace industries. PAL will provide direct supervision during these visits. Students will be encouraged to use advanced computing resources from both commercial (Amazon Web Services, Google Cloud Platform) and academic (ACENET) providers. While the core tasks of this project are data driven and computational, students will have access to Dr. Munroe's experimental stratified fluids lab for their research needs. Domain knowledge in physical oceanography and high performance computing will be obtained by the graduate students through their course work and their thesis research.

Students will be fully engaged in the activities of the project and will present their research findings at the company level and at national and international conferences. Specific academic thesis projects are planned for each student as described above in the detailed proposal section.

Graduate students are essential to cover the scope of the proposed work. While the plan is to recruit two MSc students and two PhD students, this may need to be modified depending on the availability of qualified students. In particular, students will be sought from previous degrees in physics, mathematics, physical oceanography, computer science, and/or data science. Ideally, the research group will be recruited to cover this range of academic backgrounds.

Value of the results and industrial relevance:

Provincial Aerospace Ltd.'s maritime surveillance system collects 24-hour data on iceberg locations. Improved tactical forecasting of iceberg drift (12- 48 hour forecast times) will allow the company to provide oil and gas developers in harsh climate with improved ability to predict and deal with high-risk icebergs. As a result this will lead to increased safety, increased production due to reduction in shut-down time, and reduced operational cost through reduction in unnecessary iceberg intervention. Improved drift forecasting leads not only to improved prediction of free-drift, but allows for more effective iceberg towing operations by providing information on the optimal direction of tow force application. Since ice management can be factored into the collision risk probability at the design stage (ISO 19906), long-term improvements to iceberg management effectiveness could ultimately lead to reduced capital costs for future projects.

Ocean currents, winds and waves contribute to the complicated dynamics of iceberg motion. Iceberg motion is presently forecasted using physics-based models that compute iceberg accelerations based on the forces acting on the iceberg. But even for current state-of-the-art iceberg drift models, it is a challenge to predict the detailed path of an iceberg 12 to 48 hours into the future due to uncertainties in the estimates of the driving forces.

The prediction of iceberg motion is important to PAL operations and all who operate in harsh marine conditions. Icebergs influence both the design and operation of offshore oil and gas facilities on Canada's East Coast. Ice management is used to reduce down time for floating structures and to reduce the probability of impact with fixed structures. Ice management can also be accounted for in the design process to reduce design loads and thereby to reduce the capital costs of offshore structures, while maintaining the appropriate levels of safety. Improving the prediction of iceberg movement will lead to lower costs and lower risks.

There are no patents or patents pending associated with the proposed project at this time. The scientific conclusions generated through this project would be useful to offshore petroleum operators predicting iceberg movement, planning for FPSO operations, and leading to safer, cost-efficient practices. The end product could lead to a marketable ice management software solutions.

Benefit to Canada:

As climate change continues to open up passageways thru the north, ice management is becoming more and more important to civilian safety and national sovereignty. Ensemble ice tracks would not only positively impact commercial operations across the Atlantic and North waterways but would also be vital to guiding search and rescue, policing, and military intervention activities.

This mutually beneficial collaboration between the Munroe research group at Memorial and PAL is expected to result in real industrial, economic, and environmental benefits to Canada. This research will likely result in an increase in intellectual property within Canada and will continue to establish Canada as one of the leading nations in the world in ice management. There is no other database in the world that has the depth of ice data within this program.

This project will also develop new software to be used by PAL for the commercial activity of providing iceberg management services. This will reduce costs associated with risk mitigation for the Oil and Gas operators and hence increase profits for those companies and in turn create revenue for the federal government in the form of corporate taxes and provide improved iceberg risk management, offshore production planning, and environmental protection. The outcomes of this project are applicable to operational ocean activities around the world.

An ensemble ice forecasting model is a necessary first step for many different follow on research programs including: pack ice tracks; ice field navigation; oil spill management within ice fields; and the impacts of iceberg geometry, internal waves, and oceanic eddies.