POTENTIAL ROLES FOR BUOYANCY AND MECHANICAL FORCING IN RAPID DECLINE OF ARCTIC SEA ICE

Overview

The Arctic is undergoing a large and rapid reduction of its sea ice cover and the general consensus has that this decline will continue: in fact, the consensus has that Arctic summers could be ice-free as early as 2040 (e.g., Holland et al. 2006). Global Climate Models participating in CMIP5, however, still underestimate the rate of decline of sea ice when compared with observations. There are also large uncertainties (of about 30 years) with respect to the timing of a seasonally ice free Arctic, this being linked to natural variability of the system (Jahn et al. 2016). The remaining uncertainty is linked with the physics and with processes that are not resolved by current Global Climate Models. Hypotheses that have been proposed in the literature to explain the slower simulated decline in GCMs include: i) moisture and heat release from a thinner ice cover (Li et al. 2013) ; ii) albedo reduction due to increased area covered by first year ice (Perovich et al. 2012); and iii) abrupt Arctic climate change triggered by a non-linear relationship between surface albedo and surface air surface temperature threshold around -5°C (Winton 2006). In this proposal we focus on the crucial role of under-resolved ocean mechanisms along sea ice leads and their associated heat fluxes. Along these sea ice leads (or Linear Kinematic Features) are discontinuities in the movement of ice floes and ice-ocean surface stresses. Such forcing excites near-inertial waves and narrow bands of large vertical velocities. Both can induce heat transports into the mixed layer (the former by shear-induced mixing across the base of the mixed layer and the latter in association with advection of heat from below). This adds to convective heat transport related to sea ice formation and associated brine rejection.

This project aims to improve our understanding of these processes, to assess how they might be modulating the rate of the sea ice decline, and by so doing reduce uncertainty in predictions of Arctic ice cover over the coming decades. To this end, we will develop a high resolution (1 m) non-hydrostatic model of a typical Arctic Ocean mixed layer to explicitly resolve the small scale mechanisms associated with convection, near-inertial motion, and Ekman pumping beneath ice leads. We will then use this tool to estimate the relative importance of these mechanisms on the larger scale ice mass balance of the Arctic sea ice cover. This use of high resolution numerical modeling to examine the implications of small scale, high frequency processes under sea ice leads represents a new niche of Arctic climate research. The team brings together complementary expertise in various aspects of physical oceanography essential to the project, e.g., sea ice modeling and dynamics, numerical modeling, small scale mixing processes, near-inertial waves, and climate dynamics. The project builds on previous successful collaboration between team members and is thus very likely to yield a positive outcome. Finally, this team project represents a unique opportunity to strengthen the links between the two largest oceanography departments in Quebec. This will help broaden the horizons of students at both institutions and will position us to better compete for federally-sponsored network grants when the occasions arise.

I) Scientific Quality of Research Project

1. Context

While most of the world ocean is stratified in temperature, cold regions are generally stratified in salt, this being a consequence of the near-freezing temperatures at the surface. A peculiarity of the Arctic Ocean is the existence of a Cold Halocline Layer (CHL), a layer of cold, fresh water lying above relatively warmer and saltier water below (e.g., Aagaard et al. 1981; Rudels et al. 1996). The water masses that sit below the CHL differ regionally in the Arctic. In the Eurasian Basin, a layer of Altantic origin lies directly below the CHL. In the Canada Basin, warmer summer and winter Pacific waters lie beneath the surface mixed layer and the Atlantic layer below. For this reason the layer beneath the mixed layer is referred to the Cool Halocline Layer in the Canada Basin. In both basins, a Near Surface Temperature Maximum layer formed from the remnant heat of the previous summer lie just beneath the surface mixed-layer, at the top of the CHL.

Replenishing of the CHL is related to sea-ice formation. In the relatively cold and fresh coastal seas of the Eurasian coastline, salt rejection from sea ice formation produces dense water that spills over the continental shelf and invades the open ocean, isolating the warm Atlantic layer below from the mixed layer above (Aagaard et al. 1981). Another source of the CHL is surface mixing fueled by salt rejection during sea-ice formation; this leads to convection that feeds the cold halocline layer (Rudels et al. 1996).

The CHL is crucial to the presence of multi-year ice in Arctic: it insulates the surface sea ice from the warmer layers at depth. By contrast, no cold halocline is observed below the mixed layer in the Southern Ocean around Antarctica. For this reason, there is less inhibition of vertical heat exchanges when ice forms and brine is rejected. This leads to a strong seasonality and ice-free summers in the Southern Ocean. In the Arctic, the last decades have seen a substantial warming of the Atlantic layer underlying the CHL (e.g., Polyakov et al. 2011; Lind and Ingvaldsen 2012). Rudels et al. (2004) show that, provided enough vertical mixing, the Atlantic layer would contain enough heat to melt the Arctic sea-ice cover. In this context, it is essential to understand to which extent the CHL can continue to provide insulation of the ice cover from this heat source.

Both the presence of a strong halocline and direct measurements from ice-tethered buoys have informed the traditionally held view that vertical heat fluxes in the Arctic are quite small (e.g., Rudels et al. 1996; Steele et al. 1996; Steele and Boyd 1998). For practical reasons, however, buoys are generally placed in regions where ice floes are stable; as such they do not sample heat fluxes below sea ice leads. More recent evidence does, and suggests that vertical ocean heat fluxes in the Arctic might be larger than generally assumed (McPhee et al. 2005). During winter, ice forms in newly opened leads and heat from beneath the CHL can be brought to the surface through convection fueled not only by brine rejection but more importantly by Ekman pumping. Surface heat fluxes as large as 380 W/m^2 were observed at 9.9 m depth beneath an active lead during the SHEBA experiment (McPhee et al. 2005). McPhee and colleagues hypothesized that the large vertical ocean heat flux were due to positive ice-ocean surface stress curl and associated Ekman pumping. Along the Alaskan coastline, Yang et al. (2004) showed that large Ekman upwelling associated with storms can lead to heat fluxes that extend down below the CHL. Similarly, stronger vertical heat fluxes are also observed on the Alaskan and Chukchi Plateau shelf breaks, where onshore geostrophic currents are driven by the dominant northeasterly surface winds (Carmack and Chapman 2003).

Recently Slavin, Tremblay, and Straub (2016) (hereafter STS16) showed modelling evidence that Ekman pumping driven by positive ice-ocean stress curls brings heat into the mixed layer from below. Using an eddy permitting configuration of the Mass. Inst. of Tech general circulation model (MITgcm: mitgcm.org) that covers the entire Arctic basin, they showed that strong shear strain rates are coincident with large ocean heat fluxes (200 W/m^2) at 40 m depth (Figure 1). Comparison with observations showed that wintertime “Ekman heat fluxes" along sea ice leads in the Canada Basin average to about 2 W/m^2 — enough reduce wintertime sea ice growth by about 11 cm. Along the Alaskan coastline positive ice-ocean surface stress curls are ubiquitous at the boundary between landfast ice and ice moving westward with the Beaufort Gyre, and heat fluxes of 40W/m^2 are common. Note also that this region of persistent positive ice-ocean surface stress curl sits just above the warm summer Pacific Waters that lie beneath the mixed layer (Menemenlis et al. 2005; Nguyen et al. 2009). This work highlights the crucial role of heat fluxes associated with sea-ice leads on the Arctic sea-ice retreat. These results, however, rely on parameterization of key small scales physical processes. In particular, the model relies on the hydrostatic approximation, which does not allow

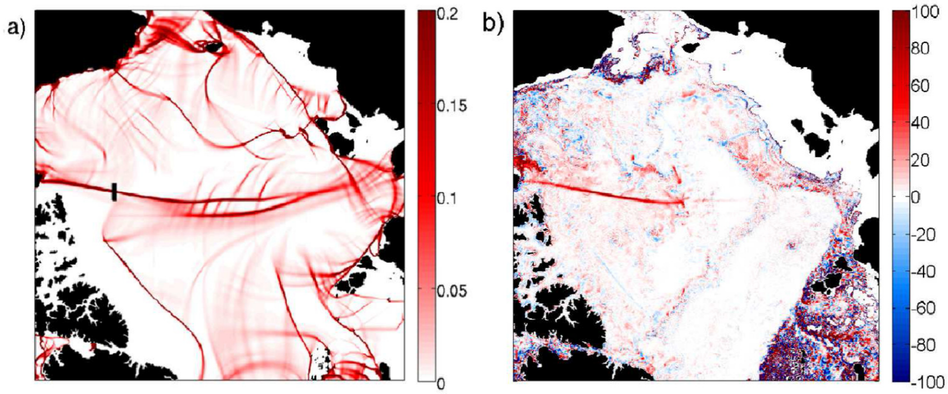

FIG. 1. (a) Spatial distribution of sea-ice shear strain rate, (b) vertical advective ocean heat flux (W/m2) at 40 m depth. From STS16

to model explicitly the active mixing layer. Thus, mixing mechanisms with spatial and temporal scales much smaller than the grid scale (e.g., upright and slantwise convection) are parameterized using stronger local vertical diffusion.

2. Objectives

The goal of this research project is to reduce the uncertainty related to the Arctic sea-ice retreat by improving our understanding of the mechanisms causing the sea ice decline. Specifically, we will perform experiments where the winter mixed layer convection beneath an active sea-ice lead is resolved explicitly, without the need for sub-grid scale parameterizations. We will also compare the relative magnitude of each physical mechanisms involved in heat transfer at the base of the mixed layer. To this end, we want to develop a high resolution (Δx =1m) configuration of the MITgcm. Results from this model will be compared with results from STS16 and from eddy resolving simulations modeling representative patches of the Arctic (Part 3, below). Our main objectives are as follows:

Part I: Estimate the mixing efficiency due to upright convection alone by imposing surface buoyancy fluxes along a line meant to represent a lead, but in the absence of any ice-ocean stress. Here, the focus will be on convection fueled by salt rejection associated with sea ice formation. We will quantify the heat transport and mixing of salt and passive scalars within the mixed layer, across its base, and below into the CHL.

Part II: Estimate the mixing and heat transport when a positive ice-ocean surface stress curl is also imposed. Different life cycle scenarios for the opening and closing of the lead with be considered. These are motivated by observations and will include scenarios that strongly excite near-inertial waves and others that do not. These same stresses, but with additional forcing to account for brine rejected due to an assumed ice formation. This will allow us to assess the combined effect of convection, Ekman pumping, and near-inertial shear-induced mixing in a stratified environment typical of the Arctic. We will do this for a range of stratification parameters bracketing realistic Arctic conditions and will then disentangle the respective roles of convection, Ekman pumping, and shear-induced mixing by modulating the amplitude and time scale over with the momentum and buoyancy forcings are applied.

Part III: Assess the relative importance of the above mechanisms on the overall Arctic sea-ice retreat. Data form the large-scale domain of STS16 will be used to construct boundary conditions for an ensemble of high resolution patches inside the large scale model. This will allow us to bridge the gap between our new small-scale configuration and the larger-scale configuration of STS16. With this downscaling method, we will estimate the heat flux associated with sea ice leads to a better accuracy by considering a statistically significant sampling of Arctic Ocean.

3. Methods

Most of the proposed work will be done using the MITgcm (mitgcm.org) numerical ocean model (Marshall et al. 1997). The specific choice of this model is twofold: (i) it is a z-coordinate model model, which is well adapted for a strongly turbulent convective environment such as the upper ocean mixing layer, (ii) it is very versatile and easy to use for idealized setups like ours. The model solves the three-dimensional primitive equations under the Bousinesq approximation on a Arakawa C-grid. The depth averaged part of the pressure is solved using a non-linear free-surface. In its non-hydrostatic configuration, a conjugate gradient 3D solver is applied to solve for the non-hydrostatic pressure. The time stepping of the thermodynamic and flow variables is staggered in time. Advection of temperature and salinity is by a second-order moment superbee flux limiter scheme (Roe 1986). An isotropic diffusion (10^{-5} m^{2}s^{-1}) is also applied to all tracers. Large eddy simulation (LES) of turbulence can be carried out using the Smagorinsky (1963) scheme for eddy viscosity, recently coded by team member L.-P. Nadeau. The sea-ice model coupled to the MITgcm includes a subgrid scale brine rejection parameterization that allows for realistic halocline vertical profiles and also reduces model bias and drift (Menemenlis et al. 2005; Nguyen et al. 2009). Note that the work proposed here does not explicitly represent sea ice; rather its motion, formation, and insulating properties are prescribed as surface boundary conditions.

The MITgcm is designed for parallel computing using horizontal tiles and allows fast integration at high resolution provided a sufficient number of CPUs. Moreover, the model is used by a large number of scientists in the international community, and as such benefits from improvements from both external users and scientists from MIT. Also, this large user base also translates to increased support for individual users, which can be useful in troubleshooting various technical problems. The model will run on the supercomputer of Calcul Quebec using 320 CPUs.

Our reference setup is designed to depict the main features of the Arctic Ocean upper ocean. The model physical domain will be a 500m square in the horizontal and 300m deep in the vertical. To explicitly resolve turbulent mixing resulting from upright convection in the mixed layer, we will use an isotropic grid resolution of $\Delta x = \Delta y = \Delta z = 1$m. In its simplest configuration (Part I), the model's boundary conditions will be doubly periodic on the sides and will be forced at the surface by fixing the temperature at the freezing point and imposing a salt flux on a narrow band in the center of the domain. This narrow band is meant to represent an ice lead. Preliminary results using this simple configuration with a uniform buoyancy flux imposed at the surface of a 200 m deep mixed layer are shown in Figure 2. Starting from rest, Rayleigh-Bénard convective cells quickly develop and the mixed layer becomes fully turbulent after about half a day. Notice that this time scale varies linearly with the depth of the mixed layer. To avoid complete mixing over time and account for the large reservoir of water below, the lower 50 m of the domain are restored to the initial density profile using a sponge layer. Note that the example shown here is an extreme one: mixed layer depths in the Arctic are typically much smaller (typically around 40 m). As such, the combination of a shallow mixed layer with relatively deep domain geometry will minimize influence of the sponge layer. Before exploring the sensitivity of the results on the buoyancy forcing, a thorough analysis of the main model parameters will be made. Dependence on numerical resolution, diffusion, viscosity and the choice of advection scheme will be performed and numerical results will be compared to observations to ensure that the model is well constrained. Vertical profiles of T and S will be initialized to the Polar Science Center Hydrographic Climatology (psc.apl.washington.edu/nonwp_projects/PHC/Climatology.html).

In Part II, a step in surface wind stress will be applied, to represent the sharp transition in ice velocity across the lead. Guided by the results of Part I, we will use the lowest resolution that does not affect the strength of convection, thus allowing us to enlarge the domain as much as possible given our computational resources. With this optimal physical domain, we will study the combined effect of salt fluxes and Ekman pumping on the heat flux across the CHL. Guided by STS16, we will also consider different scenarios for modeling the lead life cycle.

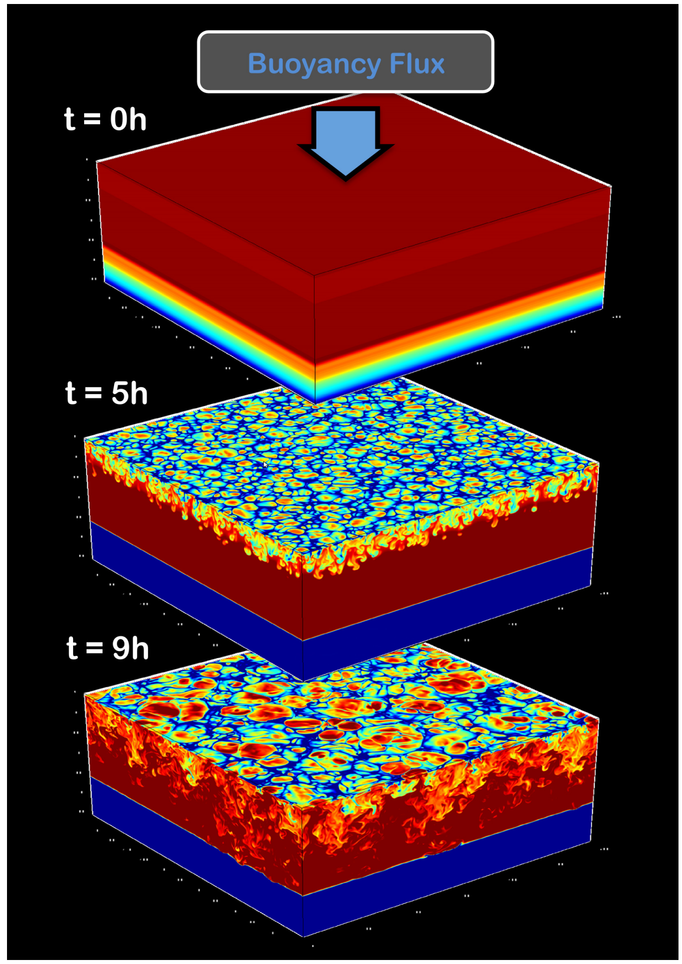

FIG. 2. Upright convection experiment: time evolution of temperature from a mixed layer profile initially at rest using the non-hydrostatic and Large Eddy Simulation version of the MITgcm.

In Part III, we will use imposed fluxes at the horizontal boundaries to replace the doubly periodic boundary conditions of Parts I and II. The hydrography from key areas inside the large-scale model of STS16 will be used to prescribe these open boundary conditions, for each high resolution patch. Before performing the ensemble simulations, we will evaluate the statistical significance of our sampling of the Arctic Ocean by analyzing the large-scale simulations of STS16. Then, drawing on knowledge gained from the results of Parts I and II, we will use our new high resolution model to parameterize the strength of the heat flux at the base of the mixed layer across the whole Arctic Ocean. The interior flow and tracers will be initialized from an interpolated version of the large scale model and allowed to evolve freely, except for a thin sponge layer near the bottom of the domain. Atmospheric forcing and sea-ice thickness will also be interpolated from the larger to the smaller horizontal grid.

4. Training of HQP

Training of HQP is an essential element to this research program. The proposed research will support two PhD students and two MSc student, all co-supervised by members of this team. PhD1 and MSc1 will be based at UQAR, while PhD2 and MSc2 will be based at McGill. The two PhD students will be funded for the whole three years period of this project. MSc1 will be funded for the two first years, while MSc2 will begin his/her research only during the last year of the project. Student projects will be closely related, thus providing synergy within the group. This promotes problem solving, as students are not isolated when confronted with technical problems. PhD1 and MSc1 will focus on Parts I and II, with PHD1 doing most of the model development and MSc1 helping to test for parameter sensitivity. PhD2 and MSc2 will be devoted to Part III of the proposal. During the initial phase of the work, PhD2 will do preliminary work on the large scale model of STS16 by evaluating a statistical significant sampling of the Arctic Ocean and developing the necessary tools to perform downscaling simulations. Following this, PhD2 and MSc2 will perform the ensemble simulations and analyze the results. All students will present their results at i) their home institution, ii) the sister institution, and iii) national and international conferences. Moreover, in order to expose the students to new ideas, each UQAR student will be invited to spend two months at McGill and vice versa for the McGill student. We anticipate being able to do this at minimal cost.

5. Planning

- *Summer 2017—Fall 2018:* Set up the model. Perform uniform forcing simulations with varying amplitude of the salt rejection to quantify the strength of turbulent mixing associated with convection alone (PhD1 — Part I).
- *Summer 2017—Summer 2018:* Perform preliminary work for Part III using the model of STS16. Evaluate a statistical significant sampling of the Arctic Ocean and develop the necessary tools to perform downscaling simulations (PhD2 — Part III).
- *Fall 2018:* Publish peer-reviewed article of the results of analysis of Part I
- *Fall 2018—Fall 2020* Study the combined effect of convection and Ekman pumping in a highly stratified ocean with localized source of heat from specified stratifications profiles (PhD1 and MSc1 — Part II)
- *Fall 2019:* Publish peer-reviewed article of the results of analysis of Part II
- *Fall 2018—Winter 2020:* Assess the relative importance of the convection and Ekman pumping mechanisms on the overall Arctic sea-ice retreat by performing an ensemble of downscaling simulations in key areas of the Arctic (PhD2 and MSc2— Part III)
- *Spring2020:* Publish peer-reviewed article of the results of analysis of Part III

II) Expected Benefits of the Project

The prospect of the opening of the Northwest Passage clearly has economic and environmental impacts for Canada's pristine north. The opening of the passage will come with an increased navigation in the region associated with exploration for ores, and shipping between eastern North America, Europe and Asia. This will provide potential for economic growth of the region. However, it could also strain the local ecosystems, and will constitute a challenge in managing economic growth while respecting local population's lifestyle and the local ecosystems.

A better understanding of the future of the sea-ice cover in the Arctic and Canadian Archipelago will give politicians a clearer picture and timeline of the future of the Arctic, helping in the planning and policy making related to its northern populations. Our proposal is well aligned with Quebec's Plan Nord, which claims "a focus on sustainable development that integrates the economic, social and environmental dimensions" (plannord.gouv.qc.ca).

The proposed research will also allow to us to assess the validity of sub-grid scale parameterizations used in current climate models. Results will then be used to better constrain the existing parameterizations and help develop new ones.

This team project represents a unique opportunity to strengthen the links between Quebec's two largest oceanography departments: McGill's department of atmospheric and oceanic sciences and UQAR's Institut des Sciences de la Mer (ISMER). The research is designed to take advantage of complementary expertise of both institutions to produce advanced search with international exposure. Researchers of this team are active members of Quebec-Ocean (quebec-ocean.ulaval.ca), the largest group of scientists involved in oceanographic research in Quebec. Members of this team also interact closely with Ouranos (ouranos.ca), a research center that aims to enable Quebec society to better adapt to climate change. Through seminars at Ouranos and Quebec-Ocean we will transfer technology and knowledge to science researchers in Quebec. The models that we develop will be made available to Quebec's research community. Finally, we will train Quebec undergraduate and graduate students in highly developed innovative numerical and physics research techniques, and animations of our results will be made available for teaching purposes at both universities.

III) Scientific Quality of Team Members

The proposed research requires a wide range of skills in various research topics: a) high latitude climate and sea ice, b) physical oceanography and geophysical fluid dynamics, c) numerical modeling and d) small scale turbulence. As each team member brings a combination of these skills, a positive outcome of this proposal thus depends on the collaboration of all the group.

B. Tremblay is high latitude climate scientist. His expertise covers: i) ocean and sea-ice modeling (both regional and global), ii) the study of air-sea interactions over ice covered seas, iii) the fresh water budget of the Arctic and iv) sea-ice transport problems in various climate applications. He has authored and co-authored more than 165 publications in peer-reviewed journals with more than 80 different collaborators. He received his PhD at McGill University in the department of Atmospheric and Oceanic Sciences in 1997. Prior to joining McGill, he spent 10 years at the Lamont Doherty Earth Observatory (LDEO) of Columbia University in New York where he held a tenured position. During his PhD, he developed a sea-ice model based on a granular material rheology that he continued to develop with many students and postdocs over the years (e.g., Lemieux et al. 2008, 2010). For his significant contribution to the field, he his now a well respected authority in the field of sea ice modeling and observation. The model he developed is presently used by various research groups around the world. Tremblay is also responsible for the Canadian Arctic Buoy Program. Tremblay has a good track record of disseminating his finding to the general public. He participated in over 40 interviews for national and international television and radio programs, newspapers and science magazines. He was also Editor for the Journal of Geophysical Research Oceans from 2007 to 2012, and has received several scientific awards (e.g. Landolt Chair, the Storke-Doherty Lectureship at Columbia University and the NOAA postdoctoral fellowship in climate and global change.

D. Straub is a physical oceanographer and brings expertise in geophysical fluid dynamics and numerical modeling. His research topics cover: i) energy transfer across scales in the ocean, ii) interaction between geostrophic and near-inertial motions, iii) loss of (geostrophic) balance iv) Antarctic Circumpolar Current and v) the origin and propagation of the quasi-zonal jets populating the mid-latitude oceans. He received his PhD at University of Washington and completed a post-doc Oxford before joining McGill in 1993. Straub has a deep insight in theoretical geophysical dynamics. He has worked on a variety of problems including both detailed looks at various dynamical mechanisms in idealized settings and modeling and analysis of complex flows in more realistic settings. Much of his recent work focuses on interactions between geostrophically balanced mesoscale motions and higher frequency motions such as near-inertial waves (e.g. Taylor and Straub 2016), which are more typical of the sub-mesoscale. His work emphasizes the importance of these interaction to the larger scale circulation. Through various collaborations, he is also involved with atmospheric problems including the effect of precipitation on the energetics of an idealized model of mid-latitude climate and comparing high resolution quasigeostrophic and Boussinesq simulations of rotating stratified turbulence near an idealized tropopause.

L.-P. Nadeau is a young physical oceanographer with expertise in numerical modeling of mesoscale processes. His research topics cover: i) the meridional overturning circulation, ii) ocean-climate interactions, iii) ocean jets and eddies (mesoscale processes), iv) the dynamics of wind-driven channel flows with topography. He received his PhD at McGill and completed two post-docs at NYU and MIT before joining ISMER in 2015. During his PhD, he developed a numerical ocean model based on the continuously stratified quasigeostrophic framework in a multiply connected domain for which he wrote a multi-grid software for solving elliptic partial differential equations. In addition to the quasigeostrophic model, he developed several high-resolution configurations of the MITgcm (e.g., Nadeau and Ferrari 2015), which he has been running on supercomputers at NYU and MIT, UQAR and CLUMEQ. More recently, he has developed a multi-scale two-way nesting approach for the MITgcm. Of particular relevance for this proposal, he also recently coded the Smagorinsky (1963) scheme of eddy viscosity in the MITgcm to allow for Large Eddy Simulation (LES) of turbulence.

D. Bourgault is a physical oceanographer with expertise in observation and modeling of small scale processes. His research topics covers: i) internal waves, ii) small scale turbulence, iii) vertical turbulent fluxes (e.g. Bourgault et al. 2011) and iv) costal oceanography. He received his PhD at McGill and completed a post-docs at Dalhousie before joining ISMER in 2009. Prior to joining UQAR, he spent six years at Memorial University, where he held a tenured position. Bourgault has expertise in the St. Lawrence-Saguenay marine system and in sampling and analyzing microstructure turbulence measurements from his Vertical Microstructure Profiler. He also has extensive experience in quantitative analysis of sea-surface patterns from shore-based time-lapse cameras as well as in carrying out nonhydrostatic numerical simulations of internal solitary waves.

IV) Compatibility of the Team Members' Skills and Expertise

The principal objective of the proposed research is to better quantify the heat fluxes through the Cold Halocline Layer, which is a very complex physical environment that involves a wide range of spatial scales. The success of the proposal relies on a strong knowledge of: i) the Arctic environment (B. Tremblay), ii) geophysical fluid dynamics (D. Straub and L.-P. Nadeau) iii) small scale turbulence (D. Bourgault). All four members have a strong expertise in numerical modeling in their respective research area.

L.-P. Nadeau and D. Straub have successfully collaborated with each other in the past. Straub was Nadeau's PhD Supervisor at McGill and they published three scientific paper together. B. Tremblay and D. Straub have recently collaborated on a study that serves as a basis for the current project (Slavin, Tremblay and Straub, 2016). There, they show that Ekman pumping through ice leads is a important mechanism for heat transfer across the CHL during winter. This study was performed at relatively high spatial resolution considering the large scale Arctic Ocean domain considered, yet at extremely coarse resolution compared to the width of typical sea ice leads. The work proposed here aims to zoom in on (specified) active leads to more explicitly resolve the dynamics stemming from this high frequency small scale forcing, and how its effect on heat transport compares to that related to brine forced convection. This is where the expertise of Nadeau and Bourgault become essential. Nadeau recently developed a Large Eddy Simulation of an idealized mixing layer to study Lagrangian particles trajectories that can be almost directly applied to this research project (Figure 2) and Bourgault has a long-standing expertise in modeling and observing small scale turbulence and mixing in cold regions.

V) Quality of the Training Environment

As mentioned above, training of HQP is a central element in this research program. Students at ISMER benefit from an interdisciplinary environment, with twenty professors split equally among four disciplines of oceanography: physics, chemistry, geology and biology. Through this exposure, they become informed on modern developments in oceanography, while gaining a deeper understanding of how their work relates to this broader picture. In McGill University's Department of Atmospheric and Oceanic Sciences, the focus is broader and includes the earth's climate and atmosphere in addition to ocean sciences. It is the largest such department in Canada with 13 active faculty. In both departments, there is a large graduate student body.

As ocean dynamics occupies a central place in this proposal, students will learn the fundamentals of geophysical fluid dynamics and will benefit not only from regular meetings and informal contact with team members, but also from visiting international collaborators. Numerical ocean modeling is also very important to the proposed research and we expect the student to become fluent with programming languages (e.g. Fortran, Matlab, Python, etc) and to take a formal course in numerical methods. They will be encouraged to become familiar with both relatively simple (e.g., quasigeostrophic) models, as well as global circulation models (GCMs). They will benefit from ongoing collaborations with Jean-Michel Campin (MIT) MITgcms primary model developer. Collaboration with researchers outside our departments is important not only for the exposure to different ideas, but also for obtaining letters of recommendation as the students careers advance. To this end we will arrange for students to meet with visiting scientists, encourage email exchanges and discussions with the MITgcm user community, and encourage students to participate and present their work and relevant national and international conferences and workshops.

Numerical resources will be made available to our students. Funding for a high performance computing (HPC) infrastructure was awarded by CFI to support a research in ocean numerical modeling at UQAR. The infrastructure includes 25 nodes of 48 multi-threading cores each, for a total of 1600 cores capable of executing 3200 tasks in parallel. It is now running and available for our research projects. Moreover, the most computationally expensive experiments will be run on the publicly available CLUMEQ supercomputers (Calcul Quebec / Compute Canada). The graduate students performing the simulations will benefit from the training courses provided by the McGill High-Performance Computing Centre and other Calcul Quebec training sessions.

Finally, as B. Tremblay is an active member of Arcticnet, students working in the group will be invited to participate in the hydrography program onboard the CCGS Amundsen, and also participate in his buoy program deployment which has just received continued funding for another 5 years.

V) Ethical Considerations

We are personally committed to the rigorous and conscientious monitoring of the production and supervision of this research. We confirm that the content of the proposed research is original and not from an external source. The suggested reviewers are third parties with whom we have no conflict of interest. The Fonds Québécois de la Recherche sur la Nature et les Technologies will be acknowledged in all oral and written communications arising from this project, as well as all other funding sources of auxiliary data used in the project. The new model developed will be made available to the scientific community and public through the MITgcm website (mitgcm.org/public/source_code.html).

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