The International Arctic Ocean Drift Study – Arctic ODS

Executive Summary

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Executive Summary and Linkages to SAON

The International polar year (IPY) was an excellent international endeavor that showed us the power of international collaboration through coordination of Arctic (and Antarctic) science. The International Arctic Ocean Drift Study (AODS) has modeled itself up the experiences a number of us had in this international collaboration and indeed from international collaborative programs prior to IPY. The large-scale questions facing the Arctic require a higher level of 'internationalization' of Artic marine research and as such we propose to coordinate periodic international field programs to address these key science questions (once every 3 to 5 years). In particular we believe that process outside of our usual continental margins are a region of the Arctic requiring further attention. We also believe it is important to more fully integrate traditional knowledge with western science knowledge as a means of increasing our temporal resolution of processes and to integrate the detailed knowledge the Inuit have of component of the system upon which they depend (e.g., Barber and Barber, 2009). This white paper summaries a proposed international multidisciplinary study aiming to provide a pan-Arctic assessment of the relative role of physical processes in controlling the rapid decline in sea ice while simultaneously investigating the consequences of these changes on attendant ecosystem and biogeochemical processes. This project would be connected with the development of a community based monitoring program in the Inuvialuit Settlement Region (ISR) as a means of engaging the 'two ways of knowing' concept.

1. Introduction

The sea-ice extent at the end of the summer melt season (September) in the Northern Hemisphere has declined at a rate of more than 11% per decade since 1979. The rate of decline increased strongly during the last 10–15 years with the sea-ice extent below the 1979–99 mean every September since 1996 and the lowest five summer extents occurring in the past five years, including a new record minimum summer extent of ~3.5 million km^2 in 2012. Declines are also being observed in the mean ice thickness since 1980, with the steepest rates of decline during the last five years of the record. The two major sea ice circulation regimes in the Arctic Basin: the Beafort Gyre (BG) and the Transpolar Drift (TD) clearly illustrate changes in position, magnitude and vorticity (e.g., Lukovich and Barber, 2006, Kwok, 2008). The circulation regimes are both affected by seasonal and interannual change in ice thickness through internal stress on the motion fields. Questions remain about connectivity between these circulation regimes, the atmospheric and oceanic forcing of this connectivity, and how these affect retention versus export of sea ice. Summer/fall conditions suggest a double gyre pattern can occur with the BG cominated by cyclonic and the TD by anticyclonic surface motion. This appears to be related to high pressure over the Pacific and low pressure over the Atlantic sectors of the Arctic (Kwok, 2008, Yang, 2006) in summer and fall. Recent evidence of increasing open water throughout the annual cycle (Barber et al. 2013) and the transformation from a MY to a FY cominated system will continue to have implications on these two dominant circulation regimes and their role in retention or export of sea ice in the Arctic.

Because of the control which sea ice exerts on the exchange of mass, energy and chemical exchanges, we can expect these changes to have wide spread implications on the Arctic marine ecosystem, physical processes operating across the ocean – sea ice – atmosphere (OSA) interface and biogeochemical processes that couple the ocean and atmosphere. We can expect these changes to have implications within the Arctic and through teleconnections to processes operating at temperate latitudes of our planet. Previous research efforts have (and currently do) addressed various elements of these processes but to date there has not been a single coordinated effort that addresses all of these processes at the pan-Arctic scale. In fact, without the recent decline in sea ice thickness, extent and summer strength, a study such as proposed here, would not have been possible. Polar science has learned a lot from preceding programs but the time has arrived to scale-up our observations and modeling studies to include the Arctic Ocean and sub-polar seas in their integrated totality. To do this we required a coordinated, unified, multidisciplinary, multination field program which will be formed around the triumvirate of a) a ship based cross hemisphere transit sampling; b) three *in situ* ice camps: one in the Eurasian Basin, one at the exit of ice in Fram Strait and one in the Southern Beaufort sea ice gyre; and c) a Lagrangian autonomous ice drifter program designed to connect process studies from a and b and extend the observations to a full annual cycle. The International Arctic Ocean Drift Study (Arctic ODS) will significantly increase our knowledge of the processes governing sea ice loss while at the same time uncovering the key ecological and biogeochemical consequences of these changes in what is arguably the most dramatic environmental change of our time.

2. Objectives

This executive summary provides overarching objectives of Arctic ODS with the expectation that specific (and more detailed) objectives, hypotheses to be tested, and requisite details regarding methods, personnel, etc., will be provided within each of individual proposals seeking support from national granting councils. Arctic ODS will address two overarching, and closely interconnected research questions:

1) *What are the relative contributions of oceanic and atmospheric forcing responsible for the observed reduction in sea ice extent and thickness, and how do these vary spatially and temporally across the Arctic Basin?*

   Ocean and atmospheric heat fluxes drive the thermodynamic evolution of the sea ice and concomitantly drive the dynamic forcing which can both grow (ridging) and ablate (export and exposure to ocean heat) sea ice within the marine icescape. Some of the ice depletion during the last decade may be due to enhanced wind-driven ice export through straits connecting the Arctic Ocean with sub-polar basins [*Rigor et al* 2000; *Smedsrud et al*. 2008]. There is also evidence of the increasingly important role of atmospheric thermodynamic forcing in shaping recent changes of the Arctic sea ice [e.g. *Laxon et al* 2003; *Polyakov et al*. 2010; *Persson* 2011] and the role of cyclones in mechanical decay of sea ice and control on thermodynamics through snow deposition [*Asplin et al*. 2012]. In addition to direct surface ice melt due to high-latitude warming, the impact of enhanced upper-ocean solar heating through numerous leads in decaying Arctic ice cover and consequent ice bottom melt accelerates the rate of sea-ice retreat via a positive ice-albedo feedback mechanism (e.g., *Perovich et al*. [2008] and *Toole et al*. [2010]). The large-scale role of this feedback is yet to be quantified. It has also been postulated that the thermal state of the Arctic Ocean interior has a profound impact on the Arctic ice pack [*Shimada et al*. 2006; *Polyakov et al*. 2010, 2011a]. The Arctic Ocean receives warm water from the Atlantic Ocean via Fram Strait and the Barents Sea and from the Pacific Ocean via Bering Strait (Figure 1). Temporal variability of the temperature and volume flux of the Atlantic Water (AW) and the Pacific Water (PW) sources influences the heat content of the Arctic Ocean interior. The mechanisms by which upward oceanic heat loss occurs determine the overall distribution of AW and PW heat throughout the entire ocean and commensurate affects on sea ice thermodynamics. *Kwok and Untersteiner* [2011] suggest that "the surplus heat needed to explain the loss of Arctic sea ice during the past few decades is on the order of 1 W/m^2". This value is comparable to the uncertainties in annual net heat flux delivered to the sea ice from the atmosphere and ocean. Our project is aimed at reducing this uncertainty and evaluating the consequences of this change in sea ice.

2) *What are the impacts of this change in sea ice on ecosystem and biogeochemical processes within the Arctic Basin?*

   Changes in the physical system are commensurate with effects on chemical and biological process operating within the Arctic marine icescape. The dramatic decline of sea ice, with its accompanying changes to the Arctic marine ecosystem, energy and freshwater balances, vertical transport, and biogeochemistry, is expected to have a strong impact on the air-sea exchange of CO_2 [*e.g. Bates and Mathis* 2009*; Rysgaard et al*. 2009*; Arrigo et al*. 2010], nutrient cycling [*Tremblay et al.,* 2011], and may lead to methane release from the ocean to the atmosphere [*Shakhova et al.,* 2010]. While much work has focused on the continental shelves and their increasing role as atmospheric CO_2 sinks [*Bates and Mathis* 2009], less is known about the deep basins. Initial estimates predicted a significant increase in CO_2 uptake as these areas became ice free [*Bates et al.* 2006], but more recent evidence has shown that they may in fact have very little capacity to absorb atmospheric CO_2 [*Cai et al.* 2010; *Else et al. in prep*.]. Given the expansion of ice-free areas into the deep basins in recent years [e.g. *Comiso et al.* 2008], it is becoming vitally important that we improve our understanding of carbon cycling in the central Arctic Ocean. Declining sea ice cover is also impacting Arctic primary producers with a combined increase in both summer stratification and light availability. Light and nutrient availability, to a large extent, dictate the amount and diversity of primary producers in ocean ecosystems [*Li et al.,* 2009]. In polar ecosystems, sea ice coverage limits the length of the productive season [*Rysgaard et al.,* 1999; *Arrigo et al.,* 2008; *Arrigo and van Dijken,* 2011] by controlling the photosynthetic light requirement. Recent evidence of a freshening Arctic Ocean and its influence on enhancing the oligotrophic state will influence the magnitude and community composition of primary producers [*Li et al.,* 2009]. Wind-driven coastal and ice-edge upwelling of nutrients may also become more commonplace. Upwelling-induced phytoplankton blooms have been observed in areas adjacent to sea ice cover in the Beaufort Sea [*Mundy et al.,* 2009]. These blooms contributed up to twice the annual primary productivity for the region, and corresponding ice-edge algae was more than three times greater than average [*Tremblay et al.,* 2011]. Melting permafrost may lead to a large increase in methane emissions from wetland areas in northern Canada and Eurasia as well as potential methane release from methane hydrates and ocean sediments [*O'Connor et al.,* 2010]. This process has already been documented along the East Siberian Shelf [*Shakhova et al.,* 2010].

The overarching ***goal*** of the international multidisciplinary Arctic ODS is to provide a pan-Arctic assessment of the relative role of physical processes in controlling the rapid decline in sea ice while simultaneously investigating the consequences of these changes on attendant ecosystem and biogeochemical processes. In terms of policy, Arctic ODS will contribute science required to inform questions such as: 1) Do we expect the current rates of sea ice decline to persist, to accelerate, or to slow down? 2) What is the relative role of the atmosphere and ocean processes in forcing sea-ice decline? What role do high frequency events (such as atmospheric cyclones and oceanic eddies) play in sea ice growth and decay? 3) What are the relative contributions of Atlantic and Pacific waters to sea ice melt and how does this upward oceanic heat transport vary geographically and temporally? 4) Will the Arctic Ocean become a source or a sink for carbon dioxide? 5) Will the Arctic Ocean become more biologically productive and if so where and why; and 6) Will the Arctic become navigable during summer in the near future? The project will facilitate better understanding of these processes during a time of the year when the region is partly covered by melting multi-year ice floes, open water, and developing first-year ice.

3. Methods

The Arctic ODS will consist of four components: i) icebreaker based transects; ii) ice camps in the eastern Eurasian Basin (EB), north of Greenland (NG), and the Southern Beaufort Sea (SB), iii) ice tethered buoys using iridium telemetry to be installed from the ice camps and during the ship transits; and iv) a modeling study which takes advantage of the field data/processes to improve our predictive capabilities. Arctic ODS is proposed to occur in 2015 with spring ice camp deployments in the Southern Beaufort Sea (SB, March-April) and near Northeast Greenland (NG, March – June) and the Eurasian Basin (EB) ice camp in September-October 2015 (Figure 1). The Canadian Research Icebreaker CCGS *Amundsen* will conduct detailed shelf-basin transect sampling through the Beaufort Gyre, across the Canada Basin to the Eurasian Shelf and from there back into the Eurasian Basin and out of the Arctic through Fram strait (Figure 1). Surveys will begin from Kugluktuk, NU on 27 August 2015 and ending with a full crew change in Point Barrow, Alaska on 17 September 2015. The ship will then transit across the Arctic Ocean to the EB ice camp, sampling and deploying drifters at stations while en route. The EB ice camp will be established over the deeper part of the Laptev Sea slope at ~125ºE (Figure 1) with expected drift into the EB interior driven by prevailing winds. The *Amundsen* will remain at the EB ice camp for one month providing logistical and safety support to this ice camp. Arctic ODS will end with a full crew change in Svalbard, Norway on 29 October 2015, and the ship will then return to its home port of Quebec City, Quebec.

3.1. Ship-based observations

Ship-based observations including in situ and underway Acoustic Doppler Current Profiler (ADCP), Conductivity-Temperature-Depth (CTD)/rosette soundings, ocean surface mixed layer nutrients, baseline zooplankton assemblages and fish abundance will be conducted. Rosette measurements will provide biophysical variables every 3-12 h while the ship is stationary at the ice camp and while in transit and provide physical oceanography variables (conductivity, temperature, density, and oxygen). Water-column measurements of the dissolved elemental pool will include the carbon system (DIC, alkalinity, pH and pCO_2), dissolved organic carbon (DOC) and nitrogen (DON) and the inorganic nutrients nitrate, nitrite, ammonium, phosphate and silicate [*Grasshoff* 1999]. Changes in these elemental pools will be compared with measurements of gas flux, DIC photo-production and nitrogen uptake to assess new, regenerated and net production. Vertical profiles of nutrients, chlorophyll and phytoplankton taxonomy will be sampled with the CTD-Rosette systems of the *Amundsen*. Fine-scale vertical profiles of mesozooplankton abundance will be recorded daily with the new Lightframe On-sight Keyspecies Investigation system (LOKI) taxonomist robot deployed from the moonpool of the ship. Fish (mostly Arctic cod) and marine mammal abundance under the ice floe and within a radius of 2.5 km around the *Amundsen* will be recorded continuously thanks to the new SX-90 fisheries sonar. Gill nets will be deployed to identify the fish responsible for the echoes.

An underway meteorological program will examine vertical profiles of temperature, humidity and wind vectors to 10km height. Four-time daily launches of rawinsondes from the *Amundsen* sensor package will provide the basic vertical characterization of the atmospheric thermal, moisture, and kinematic structure producing the observed surface fluxes, and are therefore crucial. A ceilometer will provide time series of cloud cover and cloud-base height, also key for understanding the surface radiative fluxes. An all-sky camera will provide additional documentation of cloud cover when light levels allow. A microwave profiling radiometer [*Solheim et al.,* 1998] combined with the rawinsonde data, will provide profiles of atmospheric

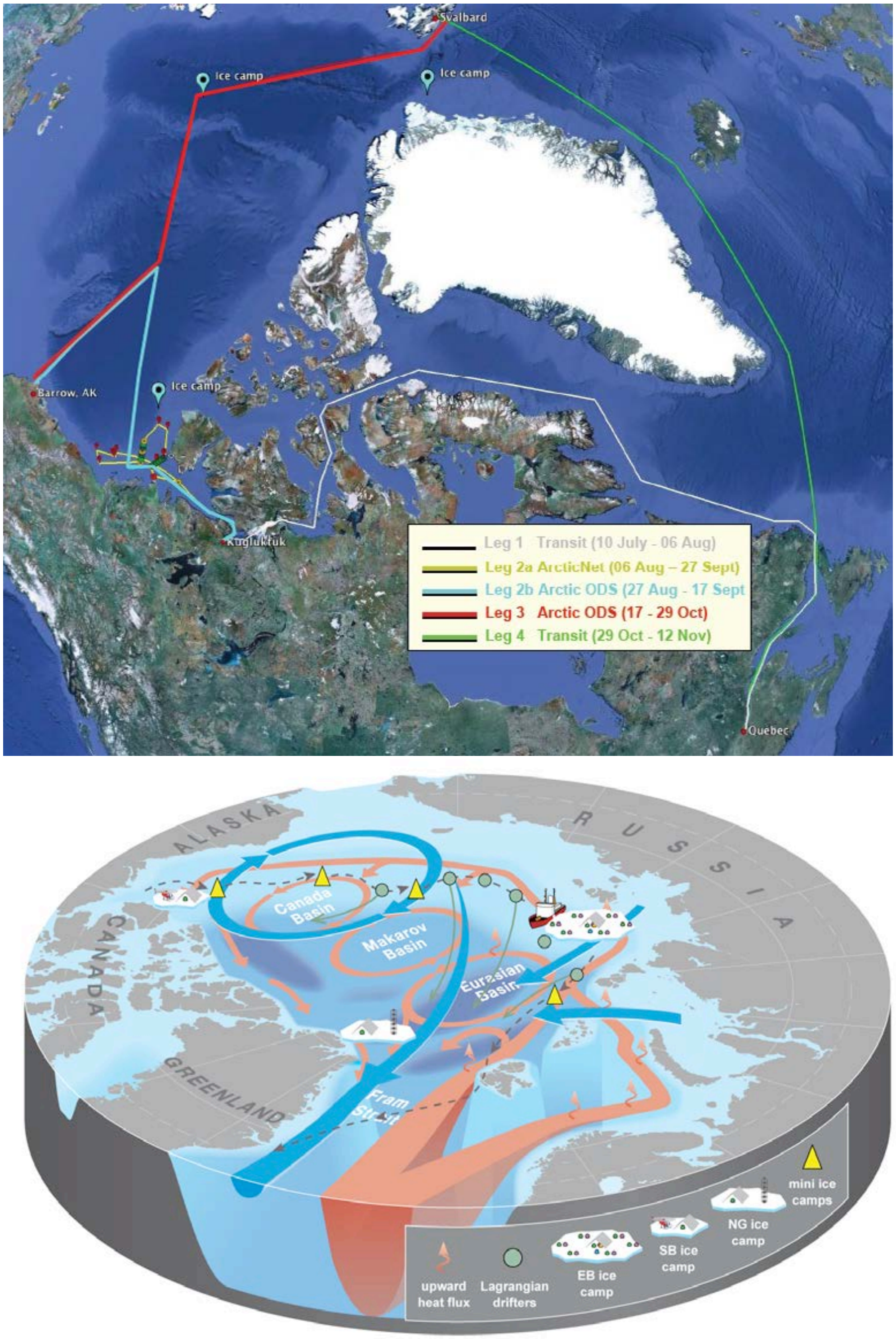

Figure 1. (Top) proposed 2015 timelines and cruise path of the research icebreaker CCGS *Amundsen*, and Arctic ODS. (Bottom) Proposed Arctic ODS field campaign. Circulation of the surface water and intermediate Atlantic Water of the Arctic Ocean is shown by blue and red arrows, respectively.

temperature and water vapor of experimental quality at higher temporal resolution than the rawinsondes and values of integrated water vapor in the expected synoptic storms, which would have significance for interpreting the surface radiation evolution. We will place an eddy covariance flux system for CO_2 and gradient sampling arrays for both CO_2 and CO on the bow of the ship to continually monitor vertical CO_2 and CO fluxes over the open water and new and mature sea ice environments of the Arctic ODS domain. Micrometeorological flux measurements will be supported by chamber deployments using both an infrared gas analyzer and syringe sampling with subsequent concentration analysis (including CH_4) by gas chromatograph. Bulk meteorology, the surface heat budget and on-track surface video will be monitored to place the gaseous carbon exchange in the context of surface ecological climatology. We will continuously monitor surface water p CO_2, using an underway sensor mounted on the *Amundsen*'s clean seawater supply, calibrated with discrete samples collected from the rosette.

A remote sensing program will use surface-based microwave radiometers (19, 37 and 89GHz), scatterometers (5.3 GHz, fully polarimetric), thermal infrared radiometers (9-11 μm), and hyperspectral optical radiometers (0.38-1.1 μm), coupled with the climate station and geophysical properties to calibrate in situ measurements to various satellite systems. Physical properties of sea ice will be measured in parallel with EM scans via on-ice measurements where ice conditions permit and in open water during transits of the Amundsen. The remote sensing program will work closely with the Canadian Ice Service and NASA to validate/calibration the Canadian Radarsat II system over a wide range of ice types and thermodynamic states. A helicopter-borne electromagnetic induction system (HEMI) will be used to measure sea ice surface and bottom topography, ice thickness and the layering of the freshwater beneath the sea ice [*Barber et al*. 2009].

3.2. Ice camp observations

Observations at all three ice camps will be conducted using a variety of automated and manual sampling techniques. The eastern Eurasian Basin (EB) ice camp will be support directly by the icebreaker CCGS *Amundsen* and will occur in September and October, 2015. The Southern Beaufort Sea (SB) ice camp will be mounted on thick multiyear sea ice off the NW flank of the Canadian Arctic Archipelago (CAA) using the community of Sachs Harbour, N.W.T. as the launch point for helicopter and twin otter support to this camp. The SB program will occur in March and April, 2015. The Northeast Greenland (NG) camp will be launched from the Danish research *Station North* in April and May, 2015. While different in details, observations at all three camps will be made using similar technologies and instrumentation thus providing means for direct inter-comparison of measured parameters.

3.2.1. Eurasian Basin ice camp

The ice camp will be established over the eastern EB slope at ~125ºE (Figure 1) with expected drift into the EB interior driven by prevailing winds. The overarching *goal* of this ice camp is to quantify the relative roles of lower atmosphere energy fluxes (including atmospheric heat uptake by the upper ocean) and heat transports in the ocean interior in setting the net energy flux to, and mass balance of the sea ice in the eastern Eurasian Basin (EB) of the Arctic Ocean. The proposed program focuses on the oceanic, atmospheric and coupled ocean/ice/atmosphere processes that deliver heat to the sea ice. To close the heat and freshwater budgets for the camp ice floe will require accurate measurements of all atmospheric surface heat and freshwater fluxes and divergence of lateral and vertical oceanic fluxes over an ice-floe length scale. Changes of ocean heat and freshwater contents beneath the ice floe and heat, salt and water transports across the ice floe perimeter will be carefully measured; particular emphasis will be made on measurements in the upper mixed layer. The ice camp will be used as a natural laboratory for testing scientific hypotheses on the role of various processes including large-scale intrusions, double diffusion, vertical shear of velocity etc. in shaping the oceanic upward heat fluxes; for this purposes we plan a fine monitoring of evolution of processes in the upper 300m of water column. Several sites around the ice floe will be used to define the rate and mechanisms of atmospheric heat pumping into the upper mixed layer. Impact of surface heterogeneity on absorption of atmospheric energy by the ocean and ice will be evaluated using *in situ* measurements complemented by aircraft and satellite data. These regional measurements will be placed in the context of pan-Arctic observations utilizing large-scale transects and mini ice-camp observations made from the *CCGS Amundsen*. Improved understanding of oceanic mixing and its parameterization in the state-of-the-art models will also be among long-lasting legacies of the project. Assimilation of data collected during the field campaign will provide important guidance for the design of the Arctic Ocean observational network, making the program highly relevant to the goals of the Sustaining Arctic Observing Network (SAON) initiative.

Oceanic observations at the ice camp will be done using a hexagon array (or “polygon”) of stations with an additional station in the center of the polygon (Figure 2). The stations will be spaced ~1-1.5 km apart so that the contribution of frequent eddies which are expected to pass through the ice camp site can be assessed in our measurements of lateral fluxes. This spatial configuration of observations has multiple advantages. For example, a combination of station-based Eulerian observations with Lagrangian observations provided by glider and AUV (Autonomous Underwater Vehicle) will allow us to estimate horizontal fluxes of heat, salt and momentum, and their divergences. Polygon observations will provide key information about high-resolution horizontal derivatives in the water column – a critical element for correct estimate of water dynamics.

The core ice camp observations will be arranged about the central polygon station (Figure 2). These observations will include high-frequency (2-3 casts/hour) microstructure casts in the upper 300 m water column complemented by turbulence measurements in the upper mixed layer just below the ice (0-10 m). Meter-resolution thermistor chain with several added Conductivity-Temperature-Depth (CTD) meters covering the upper 250 m of the ocean will provide highly detailed time-depth data for discerning heat and salt fluxes. These observations will be used for evaluation of DDC and turbulent vertical heat and salt fluxes (e.g. *Kelley* [1984, 1990], *McPhee* [2008]). Microstructure observations will also be used for analysis of the role of intrusions in setting vertical and lateral heat and salt transports [e.g. *May and Kelley* 2001]. Enhanced observations in the vicinity of a selected DDC interface will be used to evaluate and improve parameterizations of heat and salt DDC fluxes. Particularly, we will investigate the role of velocity shear (e.g., mean flow, tides) on DL fluxes across the interface [e.g. *Padman and Dillon* 1991, *Padman et al.* 1992]. These observations will include high-resolution (25 cm) thermistor chain and vertical and horizontal ADCP sampling. Each polygon station (including the central one) will use ITP-based (or similar Polar Ocean Profiling System (POPS) buoys) CTD measurements in combination with Acoustic Doppler Current Meter (ADCP) observations above the AW core defined by its maximum temperature (~250-300 m). These observations will be used for evaluation of heat and freshwater content changes within the polygon volume. At the polygon perimeter these measurements, complemented by observations made by glider, will

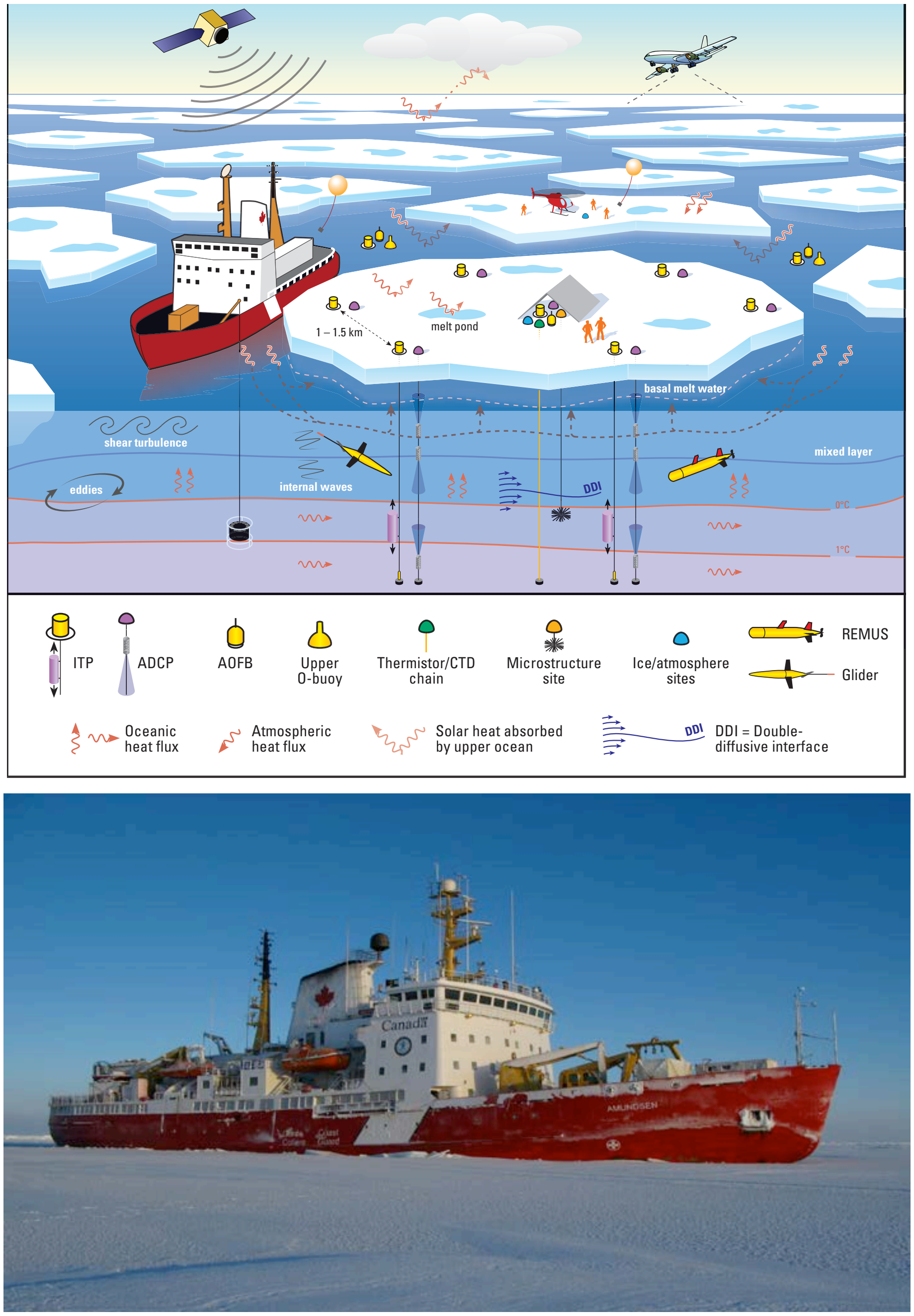

Figure 2. (Top) The proposed EB ice-camp observations. Extensive oceanic, ice and atmospheric measurements are planned at the central point of the ice floe; at the polygon perimeter oceanic measurements will provide estimates of horizontal heat, salt and momentum transports. Atmospheric heat fluxes, spatial variability in mixed-layer to ice heat exchange and various ice characteristics will be measured from the floe as well as over a wider area using helicopter surveys and distributed clusters of autonomous buoys. Spatial heterogeneity will be evaluated using *in situ* measurements complemented by remote aircraft and satellite data. The Canadian icebreaker *CCGS Amundsen* will be used as a sampling platform and a shelter for all participants of the ice camp program, providing power, laboratory space and all infrastructure for the science team.

provide estimates of horizontal heat, salt and momentum transports to close the heat and salt budgets in the interior of the polygon. At the central point these data will provide profiles of water temperature and currents required for validation of means derived from microstructure measurements. 25cm-resolution CTD chains, with several conductivity sensors deployed in the upper mixed layer, and high-resolution horizontal and vertical ADCP sampling in the upper 20 m of the water column will provide highly detailed data for discerning heat and salt fluxes (including lateral spread of atmospheric heat pumped into the upper ocean through leads). These measurements will be supplemented with ice-floe based CTD surveys of the upper ocean to characterize spatial variability in fresh water content (particularly, within the thin basal freshwater layer, Figure 2). A similar high-resolution sampling strategy will be used in the deeper part (~250 m) of each polygon station to quantify the vertical flux of heat from the AW. Gliders and AUV will document spatiotemporal changes in hydrographic structure varying on scales of several km (i.e., exceeding the local baroclinic Rossby radius) and time scales from an inertial period (~0.5 days) to several days. Ice mass balance (IMB) buoys will be installed to monitor the thermodynamic evolution of the ice through the late summer season and into the next growth year. These will include both sea ice and snow thickness evolution. Repeat surveys with helicopter-borne electromagnetic induction system (HEMI) will be used to measure sea ice surface and bottom topography, ice thickness and (in conjunction with CTD surveys) the layering of the freshwater beneath the sea ice [*Barber et al*. 2009]. Atmospheric energy fluxes will be measured at a representative site on either thick first-year or preferably multiyear sea ice. Measurements will include 4-component broadband radiometers to obtain downwelling and upwelling short and longwave radiation. Two levels of sonic anemometers and a fast hygrometer will measure the turbulent sensible and latent heat fluxes and the wind stress on the floe. Basic meteorological parameters such as surface pressure, wind speed/direction, air temperature and humidity on the floe and on the *Amundsen* are needed to characterize the near-surface environment and to provide alternative means for estimating the turbulent energy fluxes. A handful of helicopter or kite surveys with downward-pointing radiation sensors will be conducted to document the melt-pond distribution and evolution, providing the evolution of the area-averaged surface albedo, a crucial component for computing the atmospheric surface solar energy fluxes during this time of year with large surface heterogeneity. A separate flux tower will be deployed during the ice camp phase of the experiment, monitoring the evolution of the fluxes of heat and CO_2. Biogeochemical sampling will be conducted at each ice camp using the same approach as onboard the *Amundsen*.

3.2.2. North Greenland ice camp

Sampling at this ice camp will be done using in situ measurements on fast ice, and period forays into mobile ice, north of Greenland (Figure 3). An atmospheric and oceanic sampling program will be developed representing a subset and matching methodology to the EB camp (described in detail above). At the NG camp we aim to improve understanding of the processes controlling the exchange of gasses between the atmosphere and sea ice in order to enhance our capability to parameterize climate feedback mechanisms in climate models. Reduced sea ice extent has the potential to impact the exchange of greenhouse forcers (i.e. CO_2, aerosols) and precursors to greenhouse forcers (DMS) with the Arctic Ocean [*Bates et al.,* 2006]. In recent years several projects have indicated that sea ice plays an active role in the exchange of gases and particles [*Rysgaard et al.,* 2007; *Miller et al.,* 2011; *Douglas et al.,* 2012], however the magnitude and thus the importance of the air – sea ice flux is very uncertain. While an increasing number of studies of the exchange processes between the atmosphere and cryosphere over the last 10 years have taken place there is still a gap in our knowledge of especially the exchange with the marine cryosphere. Recent unpublished data from our laboratory suggests that heat fluxes between the air and surface have an important effect on the surface exchange of CO_2 but these findings require further investigation. There is an urgent need to study these processes while it is still possible to compare exchange processes over perennial ice to seasonal sea ice.

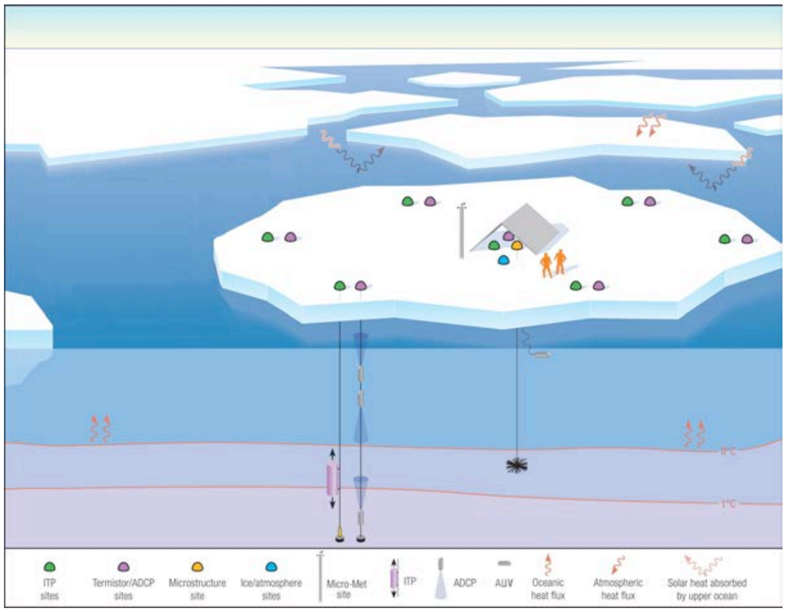

Figure 3. The proposed NG ice-camp observations which include, but are not limited to: ADCP, sea ice microstructure, micro meteorology and eddy covariance system, AUV underwater sea ice surveys, and ice-tethered profilers.

We intend to instrument fast ice and mobile ice with eddy correlation systems both for atmospheric and oceanic fluxes of gas and energy. We will study gas fluxes (CO_2, DMS and others) over the sea-ice to enhance knowledge of the processes controlling gas fluxes over this specific surface for parameterizations in climate models. In order to investigate which parameters are controlling the fluxes we will measure the fluxes and relevant parameters hypothesized to affect the flux over different types of ice, over leads and polynyas. Air-ice and Ocean-ice fluxes of greenhouse gases and precursors will be measured on the multiyear sea ice and seasonal sea ice using transferable flux systems. Profiling ADCP's, current meters, and CTD's will be used to measure heat fluxes to the base of the sea ice. In addition, profiling CO_2 probes, vertical collection of water samples and brine traps will be used to obtain information on the vertical transport of biogeochemical components below sea ice to deeper water layers. The physical and chemical properties of the ice (temperature, microstructure, brine volume, salinity, and carbonate system) will be measured as vertical profiles and measurements of solar radiation and heat fluxes above and below the ice will also be conducted. Biological CO_2 drawdown during primary production in sea ice and surface oceanic waters also affects the air-ocean gas exchange. Thus, quantification of the primary production and microbial activity (aerobe and anaerobe) using state-of-the-art techniques will be made. In order to investigate the heterogeneity of the surface (i.e. distribution of leads) we will make use of small unmanned aerial vehicles

(UAV). These can be used for sensing the surface temperature over the area within the footprint of our measurements. Furthermore we will explore the possibility of using surface images obtained from the UAV of surface temperatures over larger areas to up-scaling the CO_2 surface flux. This will be the first attempt to upscale CO_2 fluxes over a larger sea ice region.

3.2.3. South Beaufort ice camp

Sampling at this ice camp will be done using in situ measurements on thick, mobile multiyear sea ice northwest of Banks Island, N.W.T. Canada. An atmospheric and oceanic sampling program will be developed representing a subset and matching methodology to the EB and NG camps (described above). The ice in this region follows the anticyclonic rotation of the Beaufort Gyre, and typically contains some of the oldest, thickest multiyear sea ice in the Northern Hemisphere. The goal of this ice camp is therefore to improve our understanding of ocean-sea ice-atmosphere interactions in late winter through investigation of the following areas: 1) Sea ice dynamic and thermodynamic forcing, 2) Separation of the relative role of the ocean and atmosphere to ice forcing; 3) determine early season exchange of climatically relevant gases through across the Ocean-sea ice-atmosphere interface and 4) to determine early season nutrient and primary production estimates as a winter benchmark. Sea ice thicknesses and thickness distributions will be assessed via physical sampling using a sled mounted EM induction system, a Kovacs Enterprises coring system and ice thickness tape, along with rates of sea ice drift using POBs (position-only beacon). Two IAOOS drifting platforms will be also deployed, and will be left with the POBS to drift into the melt season. Meteorology will be measured at a representative site on either thick first-year or contrasting multiyear sea ice. An automated weather station will collect standard meteorological variables, such as wind speed and direction, atmospheric pressure, air temperature, relative humidity, etc. Radiation and surface energy budgets will be assessed using 4-component broadband radiometers to obtain downwelling and upwelling short and longwave radiation. Profiling ADCP's, current meters, and CTDs will be used to measure heat fluxes to the base of the sea ice, along with a profile of under-ice currents (ADCP). We will also investigate the optical properties of the ocean column under varying thicknesses of sea ice using a PAR sensor, and an underwater optical spectral radiometer (ASD). The physical and chemical properties of the ice (temperature, microstructure, brine volume, salinity, and carbonate system) will be measured as vertical profiles and measurements of solar radiation and heat fluxes above the ice will also be conducted. Biophysical processes within and under the sea ice will be investigated throughout the duration of the ice camp and will conducted in concert with the physical ocean sampling program. Ice algae will be assessed by extracting a full ice core, and assessing the ice algae content. Dissolved nutrients in the under-ice ocean column critical to primary productive (Oxygen, nitrogen, etc.) will also be monitored via regular physical sampling.

3.3. Ice tethered buoys

Lagrangian buoys will be deployed along the *Amundsen* trajectory, thus utilizing unique opportunity to deploy the buoys at strategically important Arctic Ocean locations and providing the longest drift trajectories through the eastern Arctic Ocean (Figure 1). These buoy observations, an essential part of this project, will provide vital spatial coverage for interpretation of distributed program's observations. Lagrangian drifters will be a part of long-lasting legacy of the proposed program. Ice tethered buoys (ITB's) will record a variety of processes autonomously through iridium telemetry. These will include position only ice beacons POBs), ice-mass buoys (IMBs), sub-sea ice CTD and ADCP profiling, high resolution 3-D waves in ice buoys (3D-WII) and surface meteorology (air pressure, winds, shortwave energy, temperature, etc). These ITB's will be left to continue broadcasting information at all three ice camps after each ice camp is completed in order to monitor the evolution of the system into and through adjacent seasons. Several ice position-only beacons (POBs) will be deployed in a triangular array to provide information on the higher order moments of ice motion relative to measured oceanic and atmospheric forcing (e.g., divergence, convergence, shear). These triangular beacons will be deployed in the south, cental, north and western limits of the Beaufort Sea Ice Gyre (BG) and at the beginning, middle and exit (Fram strait) of Transploar drift (TBD) stream. The 3D WII beacons will be deployed in the southern limb of the BG, central BG and in the center of the TPD to collect data on the effects of waves in ice. An automated buoy measuring atmospheric winds, temperature, humidity and surface temperature will be used in order to estimate atmospheric turbulent heat fluxes by bulk techniques at the same install locations as the ITBs. All of the ITB's will be deployed by helicopter, or directly from the ship, and the initial thickness distribution and morphology of the ice within the triangle will be measured with the helicopter EM system, and evolution characteristics monitored using remote sensing data.

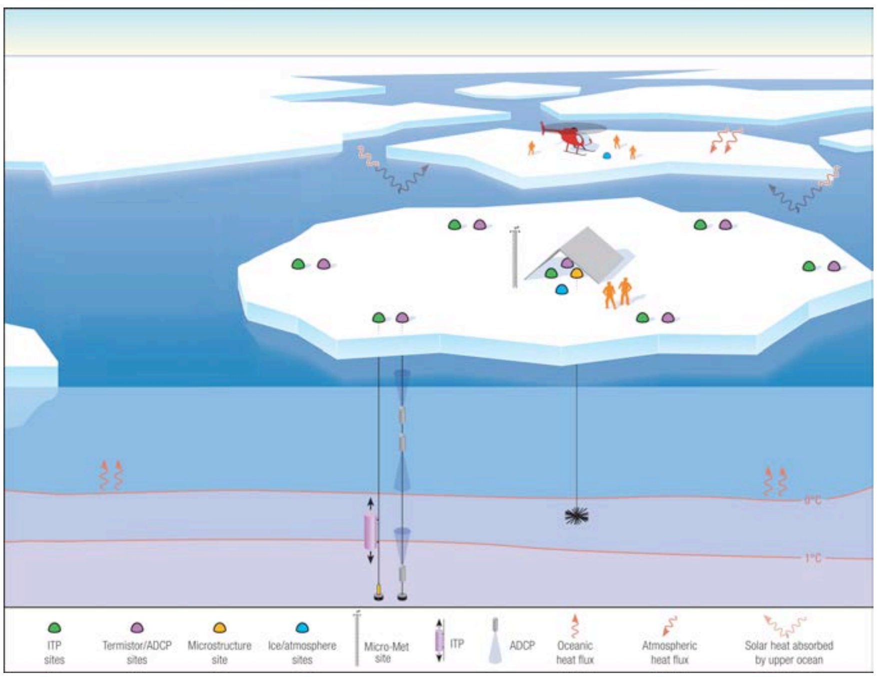

Figure 4. The proposed SBS ice-camp observations which include, but are not limited to: ADCP, sea ice microstructure, micro meteorology and eddy covariance system, and ice-tethered profilers.

Arctic ODS is also partnering directly with the French led IAOOS program (www.iaoos-equipex.fr). The main objective of the IAOOS project is to provide and to maintain an integrated observing system over the Arctic Ocean to collect synoptic and near real time information related to the state of the upper ocean, the lower atmosphere and the Arctic sea-ice. These data are complementary to satellite observations and models. In the ocean we are targeting the first 1000m beneath the surface to document precisely the surface mixed layer, the halocline and the Atlantic and/or Pacific water masses advected into the Arctic Ocean via Fram Strait and Bering

Strait respectively. We will also observe temperature profiles through the air-snow-ice-ocean interfaces and the snow-sea-ice thickness as a function of time in order to control sea ice melting and freezing. In the atmosphere we do not have actually any system able to profile throughout the troposphere and up to the stratosphere except from satellites. However, profiles obtained in the lower troposphere from satellites are subject to errors and bias. The IAOOS drifters will use upward looking LiDAR technology to address this limitation. These instruments can be validated using the upward looking microwave profiling radiometer, and rawindsondes, onboard the *Amundsen* at the time of deployment.

The IAOOS system will involve 15 autonomous platforms operating at any given time in the Arctic Ocean for a period of 5 years in total (2014-2019). Each platform will be composed of 3 elements for oceanographic, sea-ice and atmospheric vertical soundings. The platforms are designed to float at the surface of the ocean as well as to remain on top of sea-ice floes. Each IAOOS platform has a two-year lifetime. The fifteen IAOOS platforms will be drifting according to sea-ice motion, surface winds and ocean currents and it will be necessary to replace part of the fifteen platforms every year. It is anticipated that 5 platforms will either drift away from the central Arctic Ocean through Fram Strait or be destroyed by sea ice rafting or ridging every year. It is planned to replace 5 platforms every year during five years following an initial deployment of fifteen platforms in 2014-2015. This will amount to a total of 40 IAOOS platforms for the entire duration of the experiment. We expect to deploy 5 drifters during the Arctic ODS expedition and to deploy two of them at the SB ice camp.

3.4. Process studies and modeling

This part of the program will be conducted following conclusion of the Arctic ODS field programs. Physical oceanographic, atmospheric, and biogeochemical processes that we examined in project elements 1 – 3 will be evaluated and integrated into a variety of local and regional scale climate models, such as Nucleus for European Modeling of the Ocean (NEMO), and the Global Environment Multi-scale Model – Limited Area Model (GEM-LAM; Arctic Region). NEMO is a modeling framework designed for oceanographic research, operational seasonal forecasts and climate studies. It's been widely used by more than 27 countries. NEMO contains an ocean general circulation model Ocean PArallelise (OPA) coupled with a sea-ice model LIM2 (Louvain-la-Neuve Ice Model). In our study, the region covers the entire Arctic Ocean and North Atlantic Ocean in order to encompass the Arctic ODS region. The grid configuration is defined by a standard model reference run, with a prescribed set of initial boundary conditions, surface forcing, and an online interpolation scheme. The resolution is ¼ degree over equator; since the NEMO grid is a non-uniform curvilinear grid, the resolution over the Arctic Ocean is about 2/3 of that over the equator. The Arctic ODS will evaluate projections for sea ice extent, thickness, and ice drift in addition to other physical parameters that will provide insight on the economic, social and environmental implications of a changing climate for northern communities. We also present plans for additional experiments that will improve our understanding of regional and small-scale processes within the Arctic Ocean, and highlight the role of the NEMO model in providing an integrated framework that complements existing field observations and traditional knowledge, and enables long-term planning.

Regional atmospheric modelling will focus on the use of the GEM-LAM model operated by Environment Canada. Testing of the regional models will rely upon near real-time radiosonde launches from the *Amundsen* and data from the climate stations both aboard the *Amundsen* and at the three ice camps. The models will be used to examine surface forcing in the region, particularly the representation of cyclogenesis and advection of cyclones passing through the region as well as boundary layer processes. We will also investigate means of data assimilation into regional couple models of ocean-sea ice-atmosphere processes. Local scale models will focus principally on a new physical-biological coupled model being developed at Laval University to examine forcing of the marine ecosystem. This model downscales a physical ocean-sea ice-atmosphere model and links it to a NPZD model and an individually based model (IBM) of the early life of Arctic cod.

3.5. Integration of the project elements

The three ice camps and the ship transects are designed to be completely complementary in both terms of temporal and spatial sampling; and physical, chemical and biological sampling. Consistent methods will be used at each camp with specific subsets of equipment being deployed at each camp, thereby allowing direct inter-comparison of fluxes and processes. The camps have been designed to cover a range of ice thickness types with the SB camp investigating the last remaining multiyear sea ice, the EB camp focused on the late season first-year and multiyear types and the NG camp sampling these same ice types as they exit the Arctic. Seasonally the SB represents a winter tie point, NG the spring and EB and late summer and fall tie points. The camp durations and locations have been selected based on many years of our collective experience to be tractable, safe and scientifically complimentary. The CCGS *Amundsen* transects will allow us to scale our observations to the hemispheric scale and to connect the science conducted at each ice camp. The ice tethered program complements all of this by providing a direct measure of this network of pan-Arctic sampling throughout an annual cycle using the Lagrangian drifters and their iridium tracking capabilities. Finally our modeling work will bring the observations from this unique study into a framework that will allow better predictive skill of the changes going on in both the physical and biogeochemical components of the Arctic Ocean.

4. Prerequisites for project success

The research team includes members from several international institutions with strong collaborative ties, extensive experience in conducting fieldwork in harsh Arctic conditions, analyzing observational data, and in synthesizing those data with modeling results. Many of the team members have worked and published together in the past, ensuring smooth coordination of individual efforts. The members of our team are active participants in other programs, which will foster synergy. Multinational support to the Arctic ODS has been expressed at the workshop held in July 2012 in Winnipeg, Canada where researchers from 10 countries met and had productive two-days discussions developing basic science plan for the proposed trans-polar icebreaker transit and ice camps. This meeting resulted in a summary of national interests and potential contributions to the project (see Appendix 1). Arctic ODS is supported by the International Study of Arctic Change (ISAC), a program of the International Arctic Science Committee (IASC).

Available instrumentation. Our program depends upon the use and expansion of existing infrastructure, including an extensive pool of scientific and logistics equipment, and established connections with shipping companies and vendors providing scientific equipment.

Available ship. The icebreaker *Amundsen* carries a comprehensive pool of state-of-the-art scientific equipment and will be used as the primary vehicle for this project. The ship will conduct surveys in transit to the ice camp location, at the site and upon exit from the Arctic. It will also support the on-ice work of the teams through access to snow machines, ARGOS landers and ITP, IMBs and POBs.

5. Deliverables

The Arctic ODS will provide estimates of atmospheric and oceanic heat fluxes to the sea ice in the region of rapid oceanic heat loss spanning a full annual cycle. We will improve understanding of the processes controlling these fluxes, thus advancing our understanding of how the high-latitude climate system works. In particular we will: develop insight into the mechanisms responsible for upward transport of heat from the AW (and potentially the PW) to the upper ocean (including double diffusive convection (DDC), lateral intrusions, and baroclinic tides); and reduce uncertainty in the double-diffusive flux laws including sensitivity to shear. Hence, this study will make an important contribution to current knowledge of the ongoing high-latitude changes and the relative role of atmospheric and oceanic heat fluxes in diminishing Arctic ice cover. The analysis of physical processes will be used to understand how the marine ecosystem responds to these processes and the associated response of primary and secondary producers. The outcomes from our study will improve physics of ocean models and will enhance predictability of the state of the Arctic region.

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