Upper ocean as a regulator of atmospheric and oceanic heat transports to the sea ice in the Eurasian Basin of the Arctic Ocean

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Summary: The rapid loss of Arctic sea-ice volume during the past few decades is consistent with an imbalance of annual-averaged net heat flux to the ice on the order of 1 W/m^2. This value is similar in magnitude to present uncertainties in estimates of Arctic Ocean heat fluxes for known processes and modeled interactions between Arctic system components. Predicting future trends in sea-ice extent and volume requires reducing these uncertainties, which arise from poor data coverage and insufficient conceptual understanding of dominant heat transport mechanisms. This White Paper identifies leading candidates for individual and coupled ocean processes that must be better understood and represented in Arctic climate models. We identify a need to focus on the Eurasian Basin of the Arctic Ocean, a poorly-sampled region (relative to the Canadian Basin) and with unique characteristics resulting in regionally large upper-ocean heat fluxes. We restrict our attention to the role of the upper ocean in setting fluxes of atmospheric and Atlantic Water heat to the sea-ice base. We then outline data collection needs and strategies for developing a comprehensive, quantitative understanding of heat transport within the upper Arctic Ocean, and heat exchanges between the ocean, sea ice and atmosphere. These studies would improve predictions of the ocean's role in a new, seasonally ice-free Arctic. Improved understanding of oceanic mixing and its parameterization in coupled models will be among the long-lasting legacies of the suggested studies.

1. Background and Motivation

1.1. Changes in the Arctic

In the last decade, the sea-ice cover in the Arctic Ocean has experienced dramatic changes in extent and volume. Since 1979, Northern Hemisphere sea-ice extent (defined as the area poleward of the 15% sea-ice concentration contour) at the end of the summer melt season (September) has declined at a rate of ~13% per decade. The rate of decline increased rapidly during the last 10–15 years, with the September sea-ice extent below the 1979–99 mean every year since 1996. The perennial ice cover decreased from 7.9×10^6 km^2 in 1980 to just 3.5×10^6 km^2 in 2012, while the multi-year extent decreased from 6.2×10^6 km^2 in 1980 to about 2.5×10^6 km^2 in 2012 [*Vaughan et al*. 2013]. *Kwok and Rothrock* [2009] used a combination of submarine and satellite records from the central Arctic Ocean to show a 1.75 m decrease of mean winter ice thickness since 1980, with the steepest rate of sea-ice thickness decline, 0.1–0.2 m/yr, during the last five years of the record. These changes culminated in the record-breaking summer ice extent minimum in 2012. Changes in the ice cover have significant, yet poorly defined, impacts on Arctic marine ecosystems and global atmospheric circulation.

1.2. Responsible factors

Carmack et al. [2015; accepted] provides a detailed review of potential controls on changing heat fluxes to the sea-ice cover as ice volume and extent declines; we summarize primary controls below.

1.2.1. *Direct atmospheric effects*

The atmosphere directly affects sea ice through momentum, heat and moisture fluxes. A large volume of Arctic sea ice is lost to wind-driven outflow at the Fram Strait every year [*Kwok* 2009]. There is no observable trend in the 28-year record (1982-2009) in ice export [*Spreen et al*. 2011; *Kwok et al*. 2013]. However, in the backdrop of a warming trend, the decline in ice thickness could be triggered by large export events [*Kwok and Rothrock* 1999], with associated enhanced transpolar drift creating a younger ice pack more vulnerable to summer melt [*Rigor and Wallace* 2004; *Nghiem et al*. 2007; *Hutchings and Rigor* 2012]. Ice motion increases in response to changes in wind stress and the reduced resistance of thinner ice to deformation. Atmospheric thermodynamics also directly influences recent changes in Arctic sea ice [e.g. *Laxon et al.* 2003; *Polyakov et al*. 2010; *Persson* 2012], while cyclones impact sea ice through mechanical decay, wave-ice interaction and snow deposition that impacts thermodynamics [*Asplin et al*. 2012; *Parkinson and Comiso* 2013].

1.2.2. *Upper-ocean processing of atmospheric heating*

Enhanced warming of the surface mixed layer (SML) by summer insolation through the increasing open-water fraction (leads) and thinner ice (including under surface melt ponds) in the declining Arctic summer ice pack leads to increasing basal ice melt in spring and summer [*Perovich et al.* 2007, 2008, 2011, 2014]. This process accelerates the rate of sea-ice retreat by a positive ice-albedo feedback mechanism [e.g., *Perovich et al*., 2008; *Toole et al*., 2010; *Hutchings and Perovich*, 2015]. Some heat from insolation may be temporarily stored in the upper ocean, but out of reach of the ice base, in a Near-Surface Temperature Maximum (NSTM) layer [*Jackson et al*. 2010] that is typically observed at depths of 10-30 m in summer. That heat may be accessed later in fall and winter by surface mixing from wind stress and buoyancy forcing, retarding winter ice growth rather than contributing to summer sea-ice loss. Due to the small, ice-floe-scale spatial heterogeneity in the surface processes related to formation of the NSTM (including basal ice melt and mixing), we do not have observations to investigate this heat budget on the temporal scales at which stratification and mixing occur.

1.2.2. *Upward transport of Atlantic Water heat by mixing*

Variability in the oceanic heat associated with the large intrusion of Atlantic Water (AW) may have a profound impact on the Arctic ice pack [*Polyakov et al.* 2010, 2011a; *Onarheim et al.* 2014]. Most of the warm (>0°C) and salty water in the Arctic Ocean intermediate layer (depth range ~150-900 m) originates from AW inflows through Fram Strait (**Fig. 1**). After entering the Eurasian Basin (EB) of the Arctic Ocean, the AW loses heat rapidly as it circulates as a boundary current along the continental slope of the EB. The mechanisms by which this rapid heat loss occurs determine the overall distribution of AW heat throughout the entire Arctic contributes to the total ocean heat available to influence sea ice evolution. The upward heat fluxes from the ocean interior are, in most areas, small and difficult to quantify; however, regional estimates exceed 1 W/m^2 (e.g., in the EB [*Polyakov et al*. 2013]) and, therefore, are comparable to the net imbalance required to explain trends in ice loss. *Polyakov et al*. [2010] argued that observed changes in the EB over recent decades facilitated greater upward transfer of AW heat to the SML, which helped precondition the polar ice pack for the extreme ice loss observed in recent years.

Quite subtle changes in mixing rates in models can lead to large changes in upper ocean properties, even including reversal of the direction of the Beaufort Gyre [*Zhang and Steele* 2007]; however, we still do not have a good sense of the distribution and efficiency of upward heat fluxes from AW. Analyses of Ice-Tethered Profiler (ITP) records from the central EB [*Polyakov et al*. 2013] suggest that the upper permanent pycnocline (below the Cold Halocline Layer (CHL) that separates the fresh and cold SML from AW) accumulates heat from the underlying AW fairly steadily from an upward flux of ~1 W/m^2 throughout the year, but the release of this heat to the SML is seasonally modulated with higher fluxes in winter when surface-driven mixing entrains into and through the CHL. This seasonal entrainment of heat into the SML averages ~3-4 W/m^2 between January and April, reducing the formation rate of new sea ice in winter. Mechanisms by which the upward AW heat flux occurs are not clear, however. The inability to accurately represent this flux (including its seasonality) in coupled climate models results in low confidence in the projected transition of the Arctic Ocean to a new climate state as a seasonally ice-free ocean.

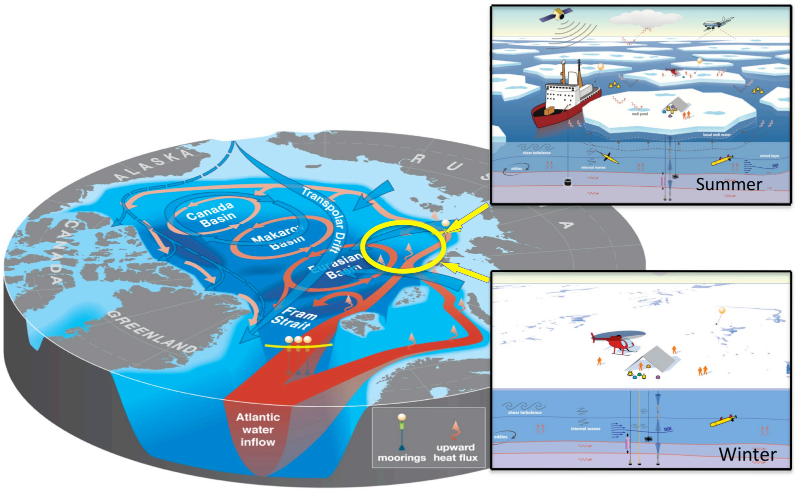

Figure 1. A suite of coordinated September-October and March-April field campaigns that would contribute to developing a comprehensive, quantitative understanding of heat transports within the upper Eurasian Basin. Circulation of the surface water and intermediate Atlantic Water of the Arctic Ocean is shown by blue and red arrows, respectively.

1.3. Regional contrasts: Canadian and Eurasian basins

The deep Arctic basins can be divided, broadly, into the Canadian Basin (CB; Canada + Makarov basins) and the EB (Nansen + Amundsen basins), separated by the Lomonosov Ridge. These regions experience distinct atmospheric, sea-ice, and oceanic conditions.

__Atmosphere__: Relative to the CB, the EB has a distinct wind regime and younger and more mobile sea ice [*Carmack et al.* 2015]. Recent poleward shift of the center of action (the center of maximum variance of the Arctic Oscillation), the atmosphere has increased its influences on the EB. For example, concurrent with decrease in the variance of North Atlantic atmospheric variability since the mid 1990s, the Icelandic low extended into the EB and the Siberian high expanded northward to the Eurasian coastal area, with which winds blow meridionally from the North Atlantic to the EB, as well as the central Arctic Ocean. Under this dynamic setting, atmospheric thermodynamic properties, such as clouds, turbulent fluxes, should have changed over this area [*Zhang et al*. 2008].

Ice: Historical observations documented large differences between the EB and CB ice covers. Russian pan-Arctic surveys in the 1950s and 1970s showed 3.5-m thick ice in the CB and 2.3-m thick EB ice [*Romanov* 1992]. This 1.2 m difference may be attributed to different atmospheric heat fluxes and temperatures between the basins. Ice circulation patterns driven by winds favor the North American side of the Arctic margin for high ice pressure and ridge-building, creating potential for very thick multi-year ice floes [*Thorndike and Colony* 1982]. The seasonal cycle of ice thickness and concentration in the CB was smaller than in the EB in the 1980s – early 1990s [*Polyakov et al*. 1999].

The situation changed around 1990, when decline of Arctic ice volume accelerated [*Rothrock et al*. 2009; *Vaughan et al*. 2013]. Satellite observations document up to 13% per decade rate of reduction in Arctic sea ice extent in September since 1979 [*Vaughan et al*. 2013]. In this period, loss of ice cover occurred faster in the CB (~16% per decade) than in the EB. Five years (2003–2008) of ICESat satellite-derived fall-winter ice thickness data demonstrated that mean thicknesses in both basins were similar during this epoch, with means of 1.95 and 1.84 m in the CB and EB respectively, in contrast to the "Old Arctic" state described in the previous paragraph. Comparison of fall vs. winter ICESat data showed the seasonal range of basin-averaged ice thickness was larger in the CB than in the EB (47cm vs. 17 cm, respectively), contrary to the Old Arctic seasonality. However, in recent years (e.g. summer 2014) sea-ice reduction in the Laptev Sea – eastern EB region was as dramatic as in the Beaufort/Chukchi area. There is a statistically significant increase of winter ice drift speed in the 2000s, which was larger in the EB [*Spreen et al*. 2011].

Ocean: In contrast to the CB, EB stratification features include a deep winter SML, a thick CHL that should impede the flux of AW heat to the upper ocean, a much larger and shallower heat source from the AW layer (150-900 m) and a lack of Pacific-sourced water in the upper ocean, a more energetic internal wave regime due to locally strong tidal currents and potential for much larger double-diffusive fluxes. In summer, the depth of the SML ranges from ~10 m in the CB to ~20 m in the EB. In winter, the regional contrast is larger, with ~30 m SML depth in the CB and >75 m in the EB [*Peralta-Ferriz and Woodgate* 2015]. Increased stratification due to freshening in the upper CB in recent years has led to suppressed thermodynamic coupling between the layer below the NSTM and the SML, as indicated by survival of the NSTM through winter in the CB [*Jackson et al*. 2011; *Steele et al*. 2011]. In contrast, recent ITP observations have demonstrated the disappearance of the NSTM in the EB, suggesting active SML-pycnocline interactions [*Polyakov et al*. 2013].

The vertical transports of AW heat vary regionally by orders of magnitude. In the central CB, AW loses heat slowly, primarily by double diffusion, with fluxes <0.3 W/m^2 [*Padman and Dillon* 1987; *Timmermans et al*. 2008]. The central CB is also a region of very low internal wave energy [*Levine et al*. 1985]. The AW in the CB is separated from the upper pycnocline and SML by a temperature minimum, resulting in little impact on the SML and ice. In the EB, highest entrainment heat fluxes are along the AW pathways [e.g. *McPhee et al*. 2003; *Sirevaag and Fer* 2009]. In the western and central Nansen Basin the AW is in direct contact with the SML and the heat fluxes are greatest, reaching tens of W/m^2. They are much smaller (but not negligible) in the EB interior: inferred estimates for the central Amundsen Basin are of the order of several W/m^2 [*Polyakov et al*. 2013]. There are several processes providing means for delivery of AW heat from the ocean interior to the upper Arctic Ocean layers. The estimated double diffusive heat flux in the EB varies from negligible in some regions with no steps, to ~1 W/m^2 in some deep-water locations in the EB [*Lenn et al*. 2009; *Sirevaag and Fer* 2012], and possibly up to ~5-10 W/m^2 along the EB margins [*Polyakov et al*. 2012a]. Internal tides in the EB can be energetic, due to strong local barotropic tide forcing [*Padman and Erofeeva* 2004], and can lead to fluxes of 10's of W/m^2 such as over the Yermak Plateau in the eastern Arctic Ocean [*Padman and Dillon* 1991; *Fer et al*. 2014].

2. Hypotheses and specific objectives

Our current understanding of the role of the upper ocean as a regulator of atmospheric and oceanic heat transports to the sea ice in the EB of the Arctic Ocean is summarized above; see, also, *Carmack et al*. [2015; accepted by *BAMS*]. Based on these reviews, we conclude that the largest sources of uncertainty and potential future changes in upper-ocean heat fluxes to the sea ice are in the EB. However, the only detailed studies specifically addressing heat flux processes in the EB have been over and near the Yermak Plateau north of Svalbard [*Padman and Dillon* 1991; Fer cite; http://tinyurl.com/o3tsceg]. In the almost three decades since then, our qualitative understanding of heat flux processes and our technical capabilities for ocean measurements have advanced greatly. With this in mind, this White Paper addresses the overarching goal to:

> *Develop a comprehensive, quantitative understanding of mechanisms by which the upper ocean regulates fluxes of atmospheric and Atlantic Water heat to the sea ice in the EB, towards improved predictions of the increased role of the ocean in a new, seasonally ice-free Arctic*.

The following Hypotheses and Specific Objectives address the principal uncertainties in fluxes and feedbacks in the EB. However, many of these apply also to the CB, and comparisons between equivalent data from both basins should prove invaluable for improving overall predictive skill of Arctic models.

2.1. Hypotheses

- H1. The size distributions of floes and leads in the EB influence the partitioning of energy and freshwater exchanges between the atmosphere, ocean and sea ice through development of secondary circulations within the SML.
- H2. Heat fluxes from the AW layer upward to the SML in the EB are dominated by the following processes, each with basin-averages exceeding 1 W/m^2: double-diffusive convection (DDC); shear in internal gravity waves excited by tidal and other flow interactions with seabed and ice-base topography; and seasonal entrainment of the upper pycnocline by SML turbulence generated by surface convection and wind stress. These processes are spatially heterogeneous and temporally variable over wide ranges of space and time scales.
- H3. Internal-wave velocity shear interacts nonlinearly with strong DDC features in the EB to modify upward heat and salt fluxes. This process is strongest over and near the EB slope; weak in the basin interior.
- H4. Baroclinic tides and the associated velocity shear and turbulent mixing are modified by the sea-ice cover, providing a feedback between upper-ocean mixing, ice concentration and thickness.
- H5. Despite positive changes in the inventories and export of nutrients and freshwater from the Siberian shelves that result from an extended open-water period, net annual primary production and CO_2 uptake will not significantly increase in the EB, due to an increase in upper ocean stratification and a decrease in shelf-slope upwelling events (especially in late summer), restricting the delivery of nutrients to the euphotic zone.

2.2. Specific Objectives

- O1. Quantify the storage and release of atmospheric heat to the EB SML and ice floe base and edges during the seasonal transition from sea-ice melt to growth.
- O2. Develop understanding of feedbacks between EB upper-ocean heat content and stratification, sea-ice properties (including thickness, lead fraction, floe scales, and snow depth and properties)

and atmospheric energy flux terms, towards identifying the role and response of these feedbacks in Arctic climate change.

- O3. Develop understanding of mixing mechanisms in, and quantify fluxes through, the EB CHL as a porous barrier between the AW and the upper ocean layers and ice.
- O4. Quantify diapycnal heat transport from the stratified EB interior to the SML from mixing associated with shear instabilities due to tides and other internal waves generated at steep topography, downward propagation of wind-forced near-inertial waves and double diffusion.
- O5. Improve parameterization of oceanic mixing in state-of-the-art models.
- O6. Develop understanding of effects of freezing sea ice on carbon and nutrient cycling, associated marine ecosystem responses, and resulting air-sea exchange processes in a time of overall sea ice reduction.

3. Recommended Actions

3.1. Overview

Our hypotheses and objectives focus on understanding individual and coupled processes controlling delivery, transport, storage and release of heat by the upper ocean in the EB, ocean interactions with the ice cover, and the broader biogeochemical implications. Addressing these requires a comprehensive observational program with strong coordination between multiple disciplines. The large seasonal variability of most system components implies the need for process studies during distinct seasons, including winter conditions with ice formation and net heat loss from the upper ocean, and a period of net radiative input to the SML representative of summer conditions. Detailed process studies are best carried out from ice camps established on sufficiently large, solid floes, either ship-supported or set up by air. Longer-term distributed observations are required to link these short-duration, localized process studies to the full annual cycle and broader region. Quantifying the relationships between heat fluxes and the resolved forcing processes requires concurrent, synergistic observations over a wide range of time and space scales that must be obtained using different types of observations and technologies (e.g., microstructure vertical profiles coordinated with spatial surveys using AUVs, multidisciplinary buoys and high-resolution aircraft and satellite observations). New measurements should be closely coordinated with existing and proposed Arctic observational and modeling efforts including the Arctic Observing Network (AON), to provide the large-scale spatial and long-term temporal coverage required for optimum data interpretation. Coordination with modeling efforts is needed for guidance in fieldwork planning and for testing parameterizations developed through fieldwork and data analysis.

3.2. Specific region

The appropriate region for EB observational campaigns is constrained by scientific needs and logistics. The winter campaign is the most challenging; helicopter-supported observations based around an ice camp provide the best option for the region and season. The recently re-opened Baranov polar station located on the northern tip of Bolshevik Island (Severnaya Zemlya Archipelago) may be a good choice as the base for helicopter operations. The area defined by a 200-250 km radius of helicopter support includes shelf, slope and deep Nansen Basin. The actual location will depend on availability of a suitable ice floe with expected drift into the eastern EB interior driven by prevailing winds. ITP #36 [see *Polyakov et al*. 2013], which started its drift in the eastern EB in summer 2009, moved ~240 km over 45 days (an average of ~5 km/day); an ice camp must remain within range of air support during this drift. The recommended sites are within the Russian Exclusive Economic Zone (EEZ).

The transition from continental slope to deep-ocean regions is a critical region for setting large-scale ocean heat fluxes; time-dependence of processes acting there (e.g., AW transport, tide forcing, eddies, intrusions and double diffusion) and interactions between them and variable sea ice cover must be understood. The EB region meets all scientific requirements for both winter and late summer - early fall campaigns. Previous observations carried out in this region were instrumental in identifying the loss of AW to and through the overlying layers, and the diffusive layering form of DDC as an important contributor for upward transport of AW heat [*Walsh et al.* 2007]. We expect an energetic ice divergence and internal wave regime due to locally strong tidal currents there [*Padman and Erofeeva* 2004]. This region is an excellent "laboratory" to study specific small-scale processes (e.g., double diffusion and internal tides) because it lacks the complications of Pacific Water and NSTM layers present in the Canadian Basin. Moreover, the EB contributes most of the ice and fresh water that flows south through Fram Strait to affect stratification in the subpolar basins where the global meridional overturning circulation originates.

3.3. Late summer/early fall process study

Hypotheses H1 and H5 and Objectives O1, O2 and O6 and (see Section 2) require measurements during transition from summer to winter (late September – October). Measurements at this time also contribute to H2-H4, and O1-O5. We argue that a heavily instrumented ship-supported ice station (see **Fig. 2**) in the EB is the best platform. Observations carried out during this campaign would facilitate better understanding of the relative role of oceanic and atmospheric heat in shaping changes of the ice cover during a time of the year when the region is partly covered by multi-year ice floes, open water, and begins to develop first-year ice. For this purpose, we require a comprehensive suite of measurements in the upper ocean (surface to ~300 m) and mass balance and atmospheric energy flux measurements over ice and open water, taking advantage of unique instrumentation developed over recent decades. Multiple sites are required to measure the energy fluxes over the heterogeneous surface at this time of year, and automated measurement systems left on the ice would provide the life-cycle context of the energy fluxes and mass changes measured during the intensive measurement period. This effort to explore the EB could be conducted in September-October of 2017, leveraging logistics already in place for the 2017 NABOS fieldwork.

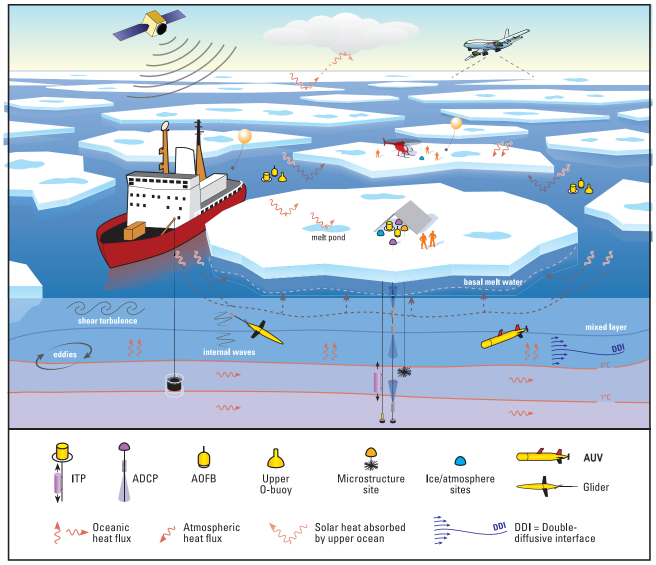

Figure 2. A suite of coordinated September-October observations centered around a ship-supported ice camp. Extensive oceanic, ice and atmospheric measurements provide critical information about atmospheric heat fluxes, spatial variability in mixed-layer to ice heat exchange and various ice characteristics from the floe as well as over a wider area using helicopter surveys and distributed clusters of autonomous buoys. Spatial heterogeneity should be evaluated using *in situ* measurements complemented by remote aircraft and satellite data. An icebreaker is 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.

Hypothesis H1 and Objectives O1 and O2 are focused on the oceanic, atmospheric and coupled ocean/ice/atmosphere processes that deliver local atmospherically-sourced heat to the sea ice. Closing the heat and freshwater budgets for the ice pack in our area of intensive survey will require accurate measurements of all atmospheric surface heat and freshwater fluxes, and divergence of lateral and vertical oceanic fluxes over the survey region. Changes of ocean heat and freshwater content beneath the ice must be carefully measured; particular emphasis should be made on measurements in the upper mixed layer (~0-10 m) close to the ice base, a depth range that is routinely missed by standard instrumentation such as ITPs. Recent studies point to large lateral variation in SML hydrographic properties determined by SML instabilities and impacts of heterogeneous surface fluxes (lead and floe scales). Measurements should, therefore, be integrated over these scales, which can be achieved by a combination of multiple sites on a floe plus lateral surveys. Options for the latter include: aircraft- and satellite-based estimates of absorption of atmospheric energy by the ocean and ice, and snow thickness; ship- and/or helo-based regional surveys; and local ("floe-scale") nearly synoptic upper-ocean surveys using gliders and AUVs.

On-floe, direct measurements of mixing rates in the SML and upper pycnocline can be obtained with ice-mounted turbulence clusters ("eddy correlation" method) at several depths across the ocean mixed layer, tethered free-fall microstructure profiles, microstructure instruments mounted on gliders and AUVs, and "Chi-pods" attached to moorings. For the latter, ice-tethered moorings could be deployed during the short-term ice-camp, but Chi-pods on traditional seabed-based moorings would also provide valuable data throughout the mooring period of 1-2 years. Each of these tools addresses distinct characteristics of ocean turbulence; as an integrated package, they provide the potential for the first "3-D" measurements of upper-ocean under-ice turbulence and mixing at floe scales.

For H5 and O6, which address biogeochemistry, the physical changes observed during this period will strongly influence nutrient inputs via a balance of stratification, upwelling and brine rejection, as very recent data strongly suggest that biological activity continues even during the polar night, contrary to the historically-held view of a "shut down". While the magnitude of any net production occurring from late summer through winter and into early spring may not be as high as that in spring and summer, biological activity in the lesser quantified seasons is likely to control which microbial groups dominate when environmental conditions become optimal.

3.4. Winter process study

The optimum time for collecting observations addressing Hypotheses H2-H4 and Objectives O3 and O4 and would be late winter, when the SML is deepest. Detailed, coordinated winter measurements are required to quantify the unique role of the CHL as a barrier to, and conduit for AW heat up to the upper ocean layers and ice in the EB. We propose that a helicopter-supported ice camp in the eastern Nansen Basin (Fig. 3) is the best option for this task. Camp duration should be 3-4 weeks, set by the need to sample a couple of storms, to assess the role of the resulting inertial-internal waves on straining and mixing in the halocline, and to monitor tidal impacts through 1-2 spring/neap cycles (14 days each). An appropriate time frame is late March – mid April. If summer/fall 2017 is chosen for the summer process study (based on coordinating with NABOS; see Section 3.3), then winter 2018 is a suitable time for this action.

Primary data collection requirements to address these hypotheses and goals include direct measurements of heat flux as a function of depth, and the full spectrum of spatial and temporal variability of the anticipated causes of ocean mixing including internal waves and the hydrographic fields supporting double diffusion. The same suite of instruments summarized in the previous section can be utilized in a winter program. Beyond the primary goals, data from tethered free-fall profilers also addresses the dynamic and thermodynamic processes driving large, basin-scale intrusions that transport AW heat and salt away from the AW boundary current into the deep basins [e.g. *May and Kelley* 2001].

For forcing fields, especially tide-generated and wind-forced near-inertial internal waves, Conductivity-Temperature-Depth (CTD) profiles, rapidly-sampling fixed-depth (*T*, *C*) sensors and "long-range" (~200 m maximum depth) ice-based acoustic Doppler current meter (ADCP) observations would document variability during the ice camp. ITPs provide a suitable automated platform for CTD profiling at high vertical resolution (~0.25 m) and can be left in place after the ice camp. Correlation of these results with time-dependent mixing rates will allow development of parameterizations relating mixing to processes that can be modeled or resolved by longer-term monitoring systems [cf. *Padman and Dillon* 1991]. One difficulty with interpreting vertical profiles of mixing parameters from drifting camps is uncertainty in the contribution of lateral advection and flux divergence; long-endurance AUVs surveying the *O*(1) km ocean structure around the camp can overcome this limitation.

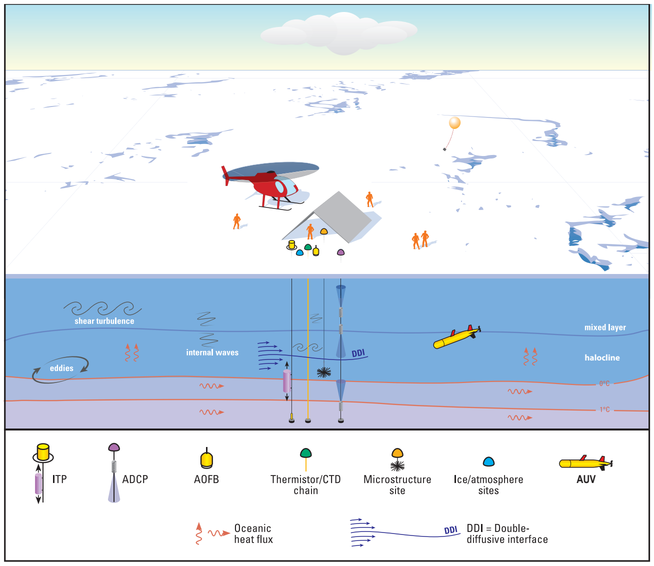

Figure 3. A suite of coordinated winter (March-April) observations centered around helicopter-supported ice camp in the EB of the Arctic Ocean. Extensive measurements are necessary to quantify the unique role of EB Cold Halocline Layer as a barrier and conduit between AW heat and the upper ocean layers and ice.

At some key heat flux "gateways" within the water column (e.g., the SML base and the CHL), we expect mixing rates to depend on finer-scale "background" state than the ITP and long-range ADCP monitoring systems can resolve: more detailed monitoring of these gateways can be provided by sensor suites such as high-resolution ADCPs with eddy-correlation sensors capable of providing high-resolution observations of velocity shear across a limited depth range. Similar equipment deployed to sample across one or more DDC interfaces would allow evaluation of heat flux response to nonlinear interactions between DDC and external shear [*Padman* 1994] such as due to internal tides [e.g. *Padman and Dillon* 1991; *Padman et al.* 1992].

3.5. Extrapolating outcomes from process studies to annual impacts across the EB

Process studies such as those recommended in Sections 3.3 and 3.4 are the principal means for advancing understanding of specific heat flux mechanisms. Quantifying the overall effect of these processes on seasonal and longer-term variability requires extrapolating the process-study results over the broader EB and through the annual cycle. I*n situ* data for broader context can be obtained from autonomous ice-mounted buoys and seabed-based moorings. Satellite and aircraft-based remote sensing provide details on sea-ice concentration, freeboard, motion and sizes and distribution of floes and leads. Resulting data sets will also contribute to initialization and validation of essential high-resolution pan-Arctic models; see Section 3.7.

Autonomous buoys: Autonomous buoys can be deployed during manned summer and winter field campaigns and by other ships of opportunity. Several buoy types are now available including:

- Ice-Tethered Profiler (ITP): high vertical resolution CTD, 1-2 profiles/day;
- UpTempO: upper-ocean and through-ice thermistor chain;
- Autonomous Ocean Flux Buoy (AOFB): turbulent fluxes just below the ice base;

- O-Buoy: atmospheric winds, temperature, humidity and snow/ice surface temperature, and atmospheric chemistry composition; and
- Ice Mass Buoys (IMB): sea ice and snow thickness evolution, temperature within the ice and snow.

A cluster of multiple buoy types could be installed at or near the central ice floe during the manned ice camps. Several distributed autonomous mini ice camps left with ITP, UpTempO, ice-mass and atmospheric buoys for over-wintering would enhance synthesis of seasonal observations. Several ice position-only beacons (POBs) deployed during each field campaign, in arrays capturing multiple spatio-temporal scales embedded in the International Arctic Buoy Program network, would provide information on the higher order moments of ice motion relative to measured oceanic and atmospheric forcing. POBs can be deployed by helicopter and the initial thickness distribution and morphology of the ice within the array may be measured with a helicopter EM system.

Moorings (seabed-based): Moorings deployed near the ice camp sites complement intensive field campaigns providing critical information about the interseasonal evolution of key processes in the SML, CHL, pycnocline and upper AW. Essential elements of the mooring design include CTD chains and ADCPs covering depth ranges essential for the project Objectives. Satlantic V2 ISUS nitrate sensors deployed alongside CTDs and additional O_2 measuring capabilities in lower halocline waters provide year-round monitoring of the quasi-conservative chemical tracers. Fixed Eulerian measurements of temporal variability of hydrography and currents, and processes such as near-inertial waves and baroclinic tides, augment the Lagrangian view of variability obtained from drifting ice camps, and provides climatologic context to the fall and winter ice camp measurements.

Satellite and aircraft remote observations of relevant parameters (ice kinematics and deformation, open water fraction, freeboard and thickness etc.) would allow us to bridge the scale between the large-scale ice cover that characterizes the EB ice pack and the sea-ice cover immediately around the ship, manned ice camps and mini-ice-camp buoy clusters. Depending on the assets available at the time of deployment, this can be achieved with different satellite and airborne instruments. Wide-swath SAR imagery (~400 km), from RADARSAT-2 (CSA) and/or Sentinel-1 (ESA), are suitable because of its relative insensitivity to weather effects. At high latitudes, these SAR satellites are capable of providing sub-daily sampling of the changes. From these images it will be possible to characterize ice deformation and open water fraction at high resolution. On cloud-free days, MODIS observations provide estimates of ice and water surface temperatures. Airborne instruments need to be coordinated to over-fly experiment sites.

3.6. Multidisciplinary opportunities

The recommended coordinated deployments focus on physical processes impacting the ocean and sea ice. However, the proposed platforms provide significant opportunities for multidisciplinary and interdisciplinary research. Ice camps, moorings, buoys, floats, gliders, AUVs, ships and satellites can carry bio-optical sensors to measure, for example, phytoplankton biomass (fluorescence), oxygen and nitrate which can then be used to estimate microbial net community production as well as particle concentration (optical absorption) and, to a certain extent, mineralogical composition (optical back scattering) of some marine particles. New sensors are being tested in temperate and polar waters for pH and pCO_2, opening the door for long-term observations related to ocean acidification, which is happening fastest in the Arctic Ocean.

3.7. Modeling component

Observational programs such as those described above must be closely integrated with modeling efforts. These range from process models (e.g., direct numerical simulation (DNS) of double diffusion; large-eddy simulation (LES) of form drag from ice keels; and brine rejection schemes for sophisticated sea ice models) to basin and global-scale simulations. The process models provide guidance to the needed data sets for developing mixing and sea-ice parameterizations; large-scale models provide opportunities to test new parameterizations, and guidance for interpreting data from local, short-term observations in the context of the likely full range of variability (e.g., of wind forcing of near-inertial waves, and baroclinic tides). With close coordination, improved understanding of oceanic mixing and its parameterization in the state-of-the-art models will be among long-lasting legacies of the project.

3.8. International coordination

Working in the eastern Arctic requires international collaboration for access and logistics. This collaboration also provides access to data sets and instrumentation, while distributing costs more broadly. Experimental design should utilize existing AON (http://www.nsf.gov/news/news_summ.jsp?cntn_id=109687) and international logistical opportunities (http://www.arcticobserving.org). Researchers from six countries met in Arlington, VA in April 2014 to discuss key science objectives for an experimental program to advance our understanding of Arctic atmosphere-ice-ocean interactions. Participants identified, as the overarching goal, development of a comprehensive, quantitative understanding of mechanisms by which the upper ocean regulates fluxes of atmospheric and Atlantic Water heat to the sea ice in the EB of the Arctic Ocean, supporting the proposed experimental program. We plan to maintain full engagement of our international partners at all stages of the program development.

3.9. Opportunities for education and mentorship

The next generation of polar oceanographers can be actively engaged in the field campaign and analysis. While the program will offer traditional opportunities for graduate students and post-docs to join the team, we will also provide opportunities for a wider community of young scientists to get involved. The centerpiece of this will be a summer school during the Fall research cruise tailored specifically to students interested in our main topics of research. We will maintain contact with these students throughout the duration of the project, developing an international network of young scientists using the data collected. It is anticipated this will enhance innovation in data analysis, interpretation and modeling. Inclusion of some of these students in the spring field campaign (numbers being small due to the logistical constraints of the campaign), follow on virtual and in-person workshops and a virtual seminar series and discussion will build collaborative links and mentoring relationships.

4. Anticipated results

A collective post-field synthesis will distill the wide range of observations, informed by modeling efforts, into a quantified assessment of the impacts of atmospheric and oceanic heat fluxes on ice cover for a region (eastern Arctic) in which ocean heat fluxes can be large and highly variable in time and space. In particular the proposed project would:

- Develop a comprehensive, coordinated data set of the physical state of the ocean and sea ice in the eastern Arctic, encompassing the broad time and space scales of forcings for lateral and vertical heat transport in the upper ocean (from the AW to the ocean surface and sea ice);
- Using direct measurements, quantify the relationships between upper-ocean vertical heat fluxes and forcing conditions and background hydrographic state for the surface mixed layer, cold halocline layer, and permanent pycnocline, and develop parameterizations for ocean heat flux based on resolved forcings;
- Quantify heat fluxes throughout the eastern Arctic and through the annual cycle by extrapolating results from process studies via the broader eastern Arctic data set and models; and
- Identify principal feedbacks between ocean heat flux mechanisms and sea-ice state, to quantify the

upper-ocean's role in the seasonal variability of eastern Arctic sea-ice state and in the longer-term trends of declining ice volume and reduced summer minimum ice extent.

The long-lasting legacies of the proposed program include:

- A comprehensive data set for ongoing model validation, initialization, and assimilation;
- Developed techniques for coordinated multi-instrument approaches to mapping ocean turbulence response to the 3-D ocean state at small scales;
- International relationships for ongoing assessment of changes in the Arctic Ocean system; and
- Development opportunities for the next generation of polar researchers.

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