Stratified Ocean Dynamics of the Arctic: Science and Experiment Plan

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1. Introduction

Vertical and lateral water properties and density structure within the Arctic Ocean are intimately related to the ocean circulation, and have profound consequences for sea ice growth and retreat as well as for propagation of acoustic energy at all scales. Our current understanding of the dynamics governing arctic upper ocean stratification and circulation derives largely from a period when extensive ice cover modulated the oceanic response to atmospheric forcing, resulting in weak seasonality, at least within the deep basins.

Recently, however, there has been significant arctic warming (*Overland et al*., 2016), accompanied by changes in the extent, thickness distribution, and properties of the arctic sea ice cover. Summertime sea ice extent has been declining since at least 1979 (when satellite-borne passive microwave sensors began providing comprehensive ice maps; *Perovich et al*., 2012), with a trend of –13.4% per decade relative to the 1981–2010 average (Figure 1; *Perovich et al*., 2015; *Thomson et al*., 2016). September sea ice minimum extents from 2007–2015 are the lowest in the 1979–2015 period, with a record minimum of 3.39 million km^2 in 2012.

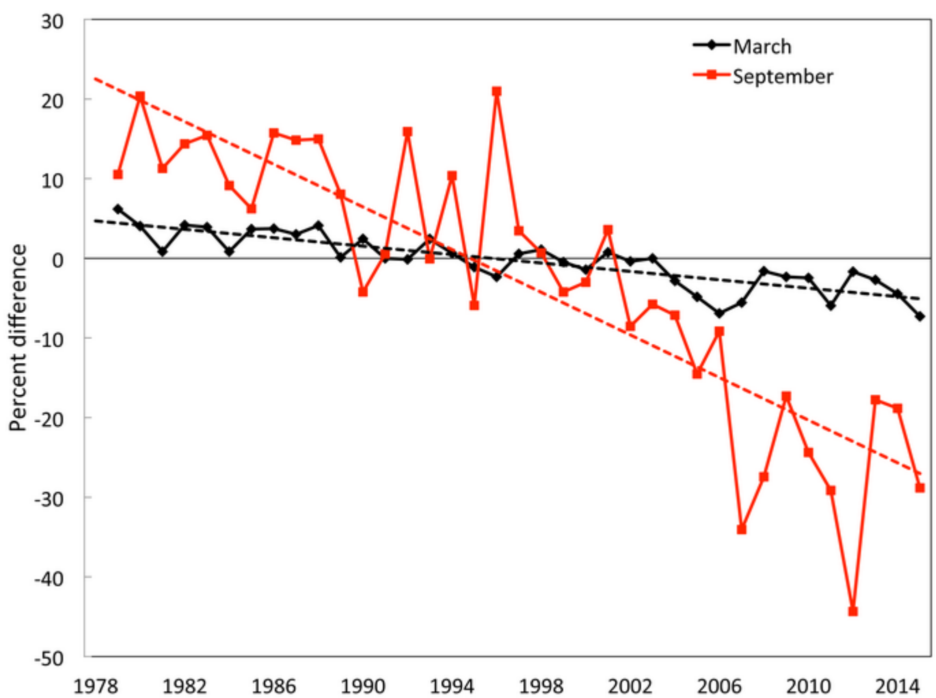

Figure 1. Time series of Northern Hemisphere sea ice extent anomalies in March (the month of maximum ice extent) and September (the month of minimum ice extent). The anomaly value for each year is the difference (in %) in ice extent relative to the mean values for the period 1981–2010. The black and red dashed lines are least squares linear regression lines. The slopes of these lines indicate ice losses of –2.6% and –13.4% per decade in March and September, respectively. Both trends are significant at the 99% confidence level. From *Perovich et al*. (2015).

Sea ice has become younger alongside the decreases in extent (Figure 2). Sea ice thickness typically increases with age, such that the combined trends toward decreasing extent and younger mean age point to a persistent loss of sea ice volume (*Kwok et al*., 2009; *Schweiger et al*., 2011). Thinner, younger ice tends to be weaker, more subject to deformation and fracturing, and thus more mobile and more likely to provide efficient coupling between the atmosphere and upper ocean. Furthermore, the growing summertime expanses of open water provide periods when the dynamics might more closely resemble those that govern the upper ocean at lower latitudes.

The need to understand these changes and their impact on arctic stratification and circulation, sea ice evolution, and the acoustic environment motivate the Office of Naval Research (ONR) Stratified Ocean Dynamics of the Arctic Departmental Research Initiative (SODA DRI).

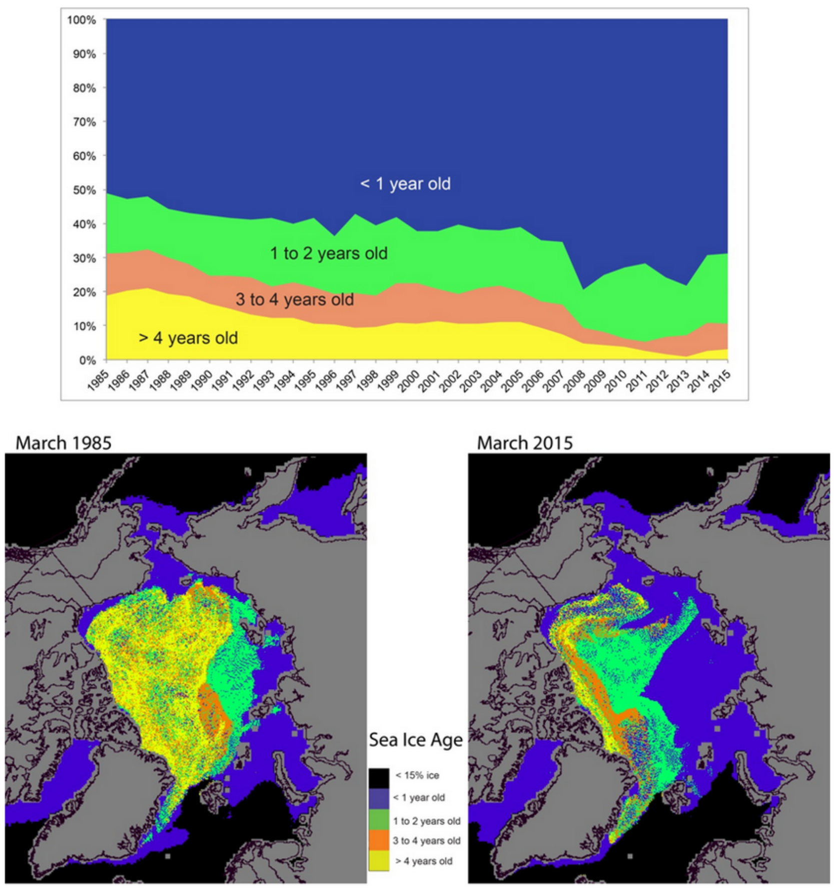

Figure 2. A time series of sea ice age in March from 1985 to the present (top) and maps of sea ice age in March 1985 (lower left) and March 2015 (lower right). From *Perovich et al*. (2015).

2. Background

The complex interplay of water mass exchange between the Arctic and subpolar Atlantic and Pacific oceans (and the inputs of shelf waters along the perimeter of the deep basin), and the local momentum and buoyancy transfers between the atmosphere, ice, and upper ocean govern Arctic Ocean stratification and circulation (Figure 3). Arctic Ocean stratification arises from a combination of horizontal advective processes and vertical mixing processes. The primary sources for arctic water masses are the saline water from the Atlantic (S~35) entering through Fram Strait and the shallower seas to its east, fresher seawater from the Pacific (S~32) entering through Bering Strait, freshwater runoff, predominately from the large Eurasian rivers, and a net positive precipitation minus evaporation (P–E). Using the salinity of the Atlantic Water as a reference, the contributions of fresh water to the basin from the Pacific Water, runoff, and P–E are similar (*Serreze and Hurst*, 2000; *Serreze et al.*, 2006). By their nature, these sources of fresh water set the stage for stratification of the Arctic Ocean through horizontal advection.

Warm, saline Atlantic Water enters through Fram Strait and the Barents Sea (Figure 4), but is soon subducted and isolated from the surface mixed layer by a cold halocline. Water mass analyses indicate that wintertime convection north of the Barents Sea provides a source of cold, saline water to maintain the halocline in the Eurasian Basin (*Rudels et al*., 1996). A different mechanism governs the Canada Basin, where brine rejection resulting from sea ice formation over the surrounding shelf regions with subsequent draining of those waters into the deep basin contributes to maintaining a shallower, broader, warmer halocline in the west (*Aagaard et al*., 1981; *Melling and Lewis*, 1982). Subduction of surface waters warmed by summertime solar input equatorward of the retreating sea ice edge is responsible for a shallow warm layer sandwiched between the cold winter mixed layer and the cold shelf-derived waters (*Steele et al*., 2004; *Timmermans et al*., 2014). Local summer heating is responsible for yet shallower warm layers within the restratifying winter mixed layer (*Jackson et al*., 2010). Riverine input along the Arctic's perimeter and inflowing low-salinity Pacific Water together with seasonal sea ice melt provide the buoyant fresh water to the mixed layer and upper halocline that stabilizes the upper ocean.

Among the most prominent features of the present-day Arctic is the amplified seasonality of sea ice extent that exposes vast regions to a broad range of ice conditions over an annual cycle (Figure 5). The Beaufort Sea embodies these changes, with dramatic northward summer sea ice retreat exposing large areas of the deep Canada Basin to periods of low ice concentration or, in the southern regions, fully open water. In 2016 the Beaufort Sea was almost ice-free. The physical processes that govern the coupled atmosphere–ice–ocean system evolve with this annual cycle in ice cover and sea ice properties (Figure 3).

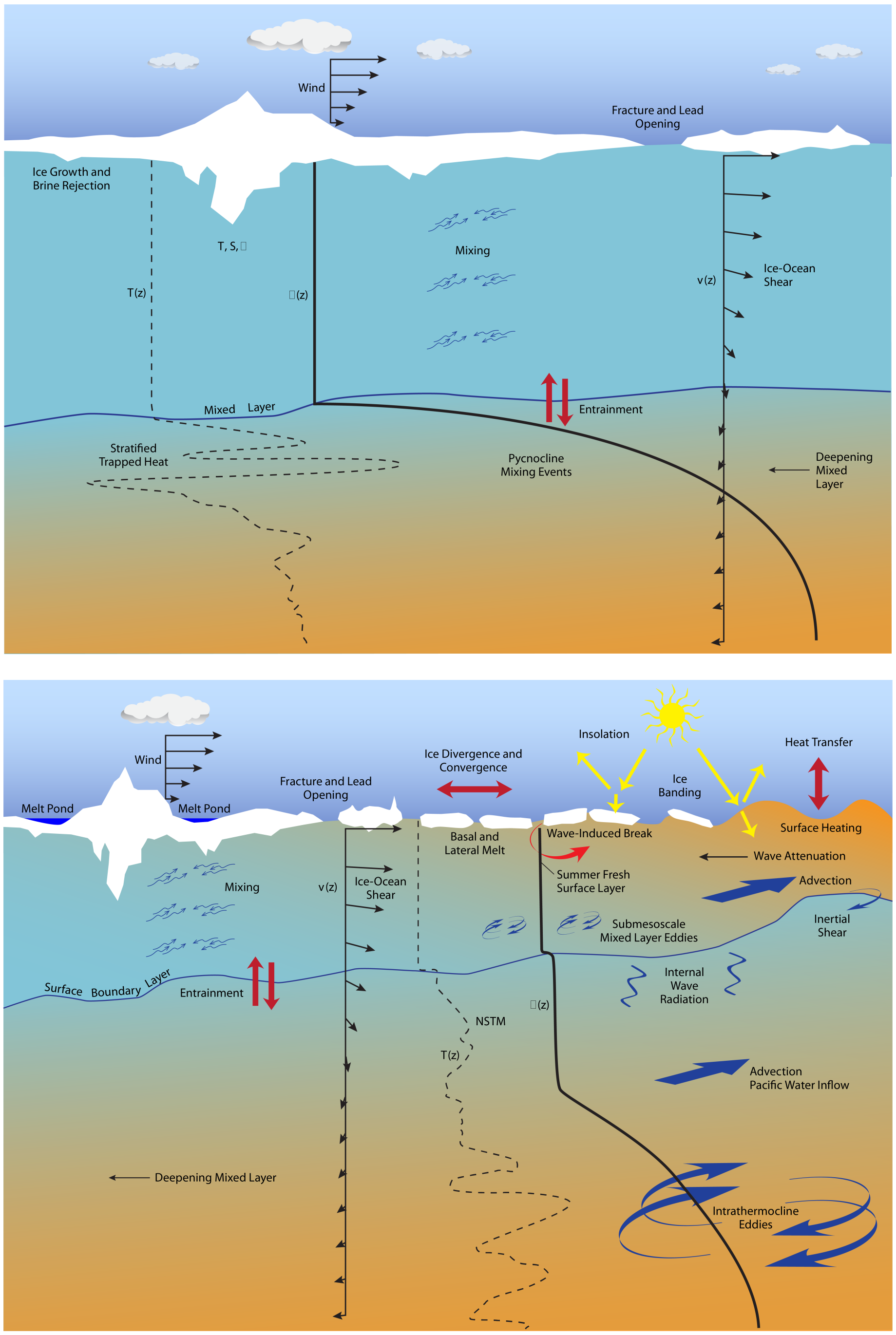

Figure 3. Winter (top) and summer (bottom) processes that govern upper ocean stratification and sea ice evolution. The interplay between exchanges of heat and fresh water with the subpolar Atlantic and Pacific, input from the shelves along the perimeter of the deep Arctic basin, and local momentum and buoyancy transfers between the atmosphere, ice, and upper ocean govern Arctic Ocean stratification and circulation. Ice cover modulates penetration of solar radiation and upper ocean response to wind forcing. The physical processes that govern the coupled atmosphere–ice–ocean system thus evolve with the annual cycle in ice cover and sea ice properties.

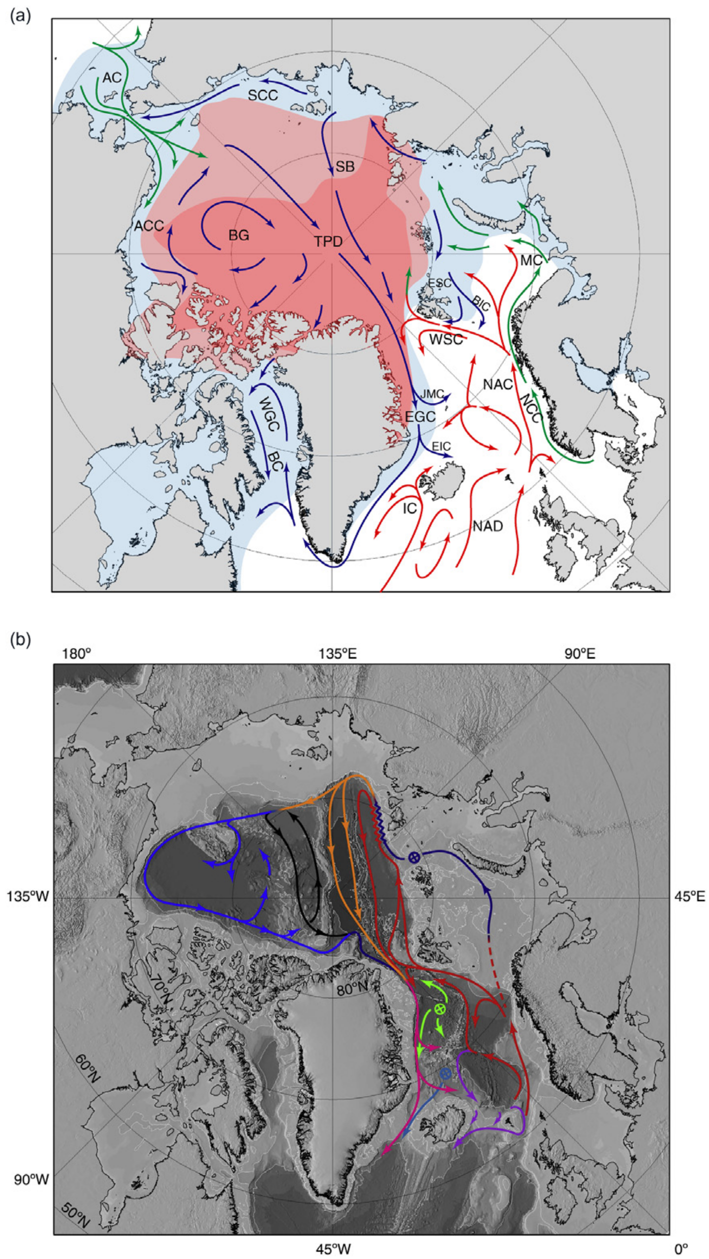

Figure 4. Circulation schematic for the arctic and subarctic seas. (a) The upper ocean. Warm Atlantic currents are indicated by red arrows, cold less saline polar and arctic currents by blue arrows. Low-salinity transformed currents are shown by green arrows. The maximum ice extent is shown in blue and the minimum ice extent in red. The 2007 sea ice minimum is shown in dark red. AC, Anadyr Current; ACC, Alaskan Coastal Current; BC, Baffin Current; BIC, Bear Island Current; BG, Beaufort Gyre; EGS, East Greenland Current; EIC, East Iceland Current; ESC, East Spitsbergen Current; IC, Irminger Current; JMC, Jan Mayen Current; MC, Murman Current; NAD, North Atlantic Drift; NAC, Norwegian Atlantic Current; NCC, Norwegian Coastal Current; SB, Siberian Branch (of the Transpolar Drift); SCC, Siberian Coastal Current; TPD, Transpolar Drift; WGC, West Greenland Current; and WSC, West Spitsbergen Current. From *Mauritzen et al*. (2013). (b) Intermediate depth ocean. The interactions between the Barents Sea and Fram Strait inflow branches north of the Kara Sea as well as the recirculation and different inflow streams in Fram Strait and the overflows across the Greenland–Scotland Ridge are indicated. From *Rudels* (2012).

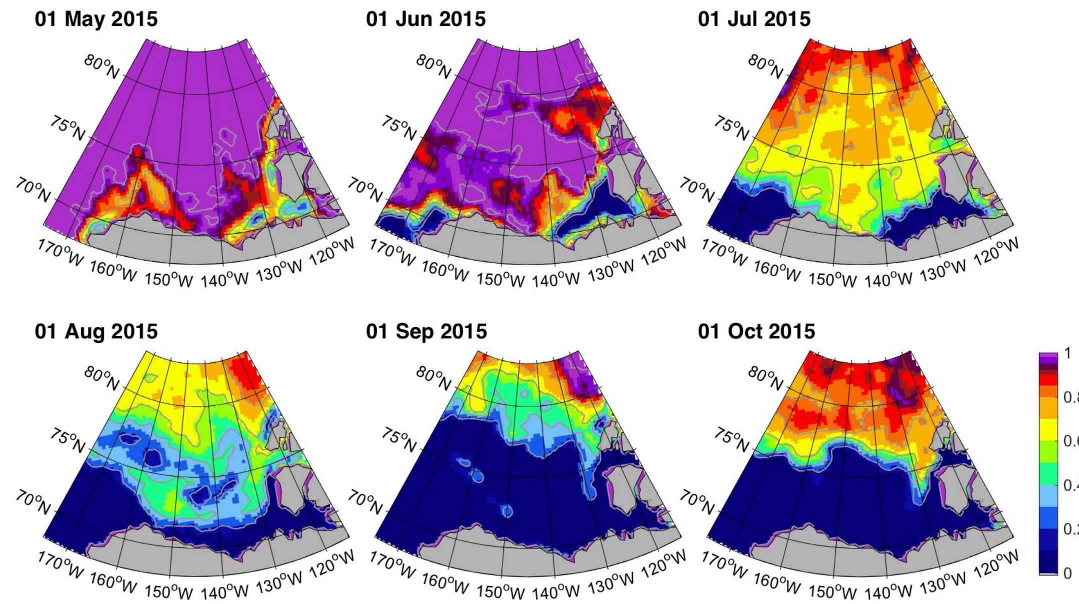

Figure 5. Annual cycle of ice concentration for 2015. The minimum in sea ice extent occurs in September. (Sea ice concentration from satellite passive microwave is provided by AMSR2, University of Bremen.)

The combination of ice cover, which modulates momentum and buoyancy transfer between the atmosphere and upper ocean, and the strong vertical density contrast created by the fresh mixed layer and cold halocline, inhibit the processes that drive diapycnal mixing. Historically, inferred mixing rates within the Arctic are one or two orders of magnitude weaker than those typically observed in lower latitude oceans (*Levine et al*., 1985; *D'Asaro and Morison*, 1992; *Plueddemann*, 1992; *Halle and Pinkel*, 2003; *Pinkel*, 2005). More direct microstructure estimates similarly indicate very small values of diapycnal turbulent mixing (*Padman and Dillon*, 1987; *Rainville and Winsor*, 2008; *Shaw et al*., 2009) and double diffusive mixing (*Padman and Dillon*, 1987; *Timmermans et al*., 2008).

Subsurface water mass modification thus occurs slowly along circulation pathways, and arctic sea ice has been largely insulated from subsurface heat carried within the Atlantic and Pacific inflows. But near the surface, variability in sea ice properties imprints onto upper ocean structure by providing a time-varying buoyancy source (fresh water and brine) and by modulating the coupling between the atmosphere and ocean (momentum and heat). For example, a consolidated ice pack greatly attenuates wind forcing of the surface ocean, while at lower concentrations, more mobile ice might efficiently transfer momentum into the upper ocean.

In turn, changes in the efficiency of air–sea momentum and heat transfer will drive changes in the processes that govern lateral and vertical exchanges in the water column. More efficient coupling between the atmosphere and upper ocean could enhance entrainment at the mixed layer base and internal wave generation. Given the contrasting water masses present in the upper ocean, enhanced vertical exchanges associated with these processes will impact stratification and circulation within the Canada Basin, with feedbacks to sea ice.

Increased open water during the summer months is changing the way the coupled physics operate in the Beaufort Sea, with changes in the wind-driven circulation, creation of surface waves and swell, and the potential for enhanced mixing and internal wave generation. These interact with changes in the inflows of Atlantic, and especially the Pacific, waters to modify the stratification and circulation within the Beaufort Sea. The recent Marginal Ice Zone DRI (MIZ DRI) focused on the impact of this increased open water fraction on the processes that control sea ice evolution within the MIZ. The SODA DRI focuses on how such changes modify the transfer of momentum and buoyancy from the atmosphere into the upper ocean, and their role in governing upper ocean stratification, circulation, and acoustic propagation within the Arctic.

2.1 Advection

The surface circulation of the Arctic Ocean is traditionally characterized by the anticyclonic Beaufort Gyre in the west and the Transpolar Drift across the Arctic towards Fram Strait in the east (Figure 4). The Beaufort Gyre, composed mainly of Pacific-derived waters in the upper few hundred meters of the water column, is driven by the time-mean anticyclonic wind stress associated with the Beaufort High in atmospheric pressure. The geostrophic component of the Transpolar Drift is aligned with a watermass front between Atlantic-derived upper ocean waters on the Eurasian side of the Arctic Ocean and Pacific-derived upper ocean waters on the North American side of the Arctic Ocean. At depths of 200-400 m, Atlantic Water circulates cyclonically in boundary currents around the major basins of the Arctic Ocean descending below the fresher, lighter Pacific-derived waters in the Canada Basin.

The Beaufort Gyre circulation has an important role in storing the fresh water that is the source of its stratification (*Proshutinsky et al.*, 2002; *Proshutinsky et al.*, 2009). The anticyclonic wind stress of the Beaufort High forces convergence of the Ekman transport of relatively fresh surface water. This domes the surface so as to drive the anticyclonic ocean circulation. From the early to mid 2000s, this doming intensified, the surface layer freshened, and the freshwater storage increased (*Farrell et al.*, 2012; *Morison et al.*, 2012; *Proshutinsky et al.*, 2009). The process has been linked to a shift of basin circulation to an increasingly anticyclonic mode as defined by the Arctic Ocean Oscillation Index (AOOI), equivalent to the sea surface height gradient across the Beaufort Gyre in a barotropic ocean model (*Proshutinsky and Johnson*, 1997; *Proshutinsky et al.*, 2001). On annual to interannual time scales, atmospheric circulation (e.g., Arctic Oscillation index) plays a large role in controlling storage, redistribution, and export of fresh water in the Arctic (*Carmack et al*., 2016). The relative distribution of freshwater export between the major exit pathways, through the Canadian Archipelago and Nares Strait or Fram Strait, is unclear. These exits lead to the Greenland and Labrador seas — regions that drive the thermohaline circulation of the world’s oceans.

Mesoscale eddies represent another lateral transport mechanism in the ocean. Eddies are believed to derive from instabilities of the larger-scale baroclinic flow field, such as the Beaufort Gyre (e.g., *Manucharyan et al*., 2016) and transport cores of anomalous water properties over significant distances. Dynamically, lateral down-gradient eddy fluxes likely balance the time-mean wind-driven convergence of low-salinity surface waters of the Beaufort Gyre. Owing to the small Rossby radius of the Arctic, these vorticies are typically quite small, around 10 km diameter (*Zhao et al*., 2014), but can have remarkably strong azimuthal velocities (several 10s of cm s^{-1}) that may modulate vertical mixing in the upper ocean.

Assessment of the eddy inventory in the Canada Basin suggests that there are now more of these features than in the past (*Zhao et al*., 2016) — a possible consequence of the intensified Beaufort Gyre baroclinicity. On still smaller spatial and temporal scales, submesoscale motions may play a role in upper ocean dynamics in the Arctic (*Timmermans et al*., 2011). These instability mechanisms act to remove small-scale lateral density gradients in the surface layer, effectively restratifying the upper ocean. When a sea ice cover is present, the surface mixed layer is held close to the local freezing temperature, precluding the development of density compensated temperature–salinity variability often observed in ice-free waters.

2.2 Vertical fluxes

Vertical heat, salt, and chemical fluxes in the stratified ocean occur principally through turbulent mixing driven by the breakdown of internal wave energy [e.g., *Gregg*, 1989; *Gregg et al.*, 2003] and double diffusive convection over depths in the halocline where both salinity and temperature increase with depth (e.g., *Padman and Dillon*, 1987; *Timmermans et al.*, 2008). The latter is manifested by a staircase-like thermohaline stratification consisting of O(1-m) thick layers separated by sharp gradient regions. The vertical temperature and salinity fluxes through these staircase stratifications, effectively set by the molecular diffusion through the staircase gradient regions, are believed to be very small.

Similarly, away from regions of strong internal tidal generation, the internal wave field in the Arctic and the associated turbulent mixing is significantly weaker than that at lower latitudes. Away from topographic features, energy levels are typically 1–2 orders of magnitude lower than observed in the mid-latitude open ocean (*D'Asaro and Morison*, 1992; *Levine et al.*, 1985, 1987). The isolation of the ocean from the atmosphere by sea ice is often cited as inhibiting atmospheric momentum transfer into the Arctic Ocean. This is certainly the case in a rigid, compact ice pack because internal ice stress absorbs some of the atmospheric momentum, but in a looser pack ice can enhance the momentum transfer from the atmosphere into the ocean (*Martin et al.*, 2014; *McPhee et al.*, 1987; *Morison et al.*, 1987).

Dissipation in the oscillating boundary layer under the sea ice has been hypothesized as an important sink of internal wave energy in the Arctic Ocean compared to ice-free seas (*Morison et al.*, 1985). It has been suggested that this increased under-ice dissipation causes a much shorter effective energy decay timescale [24 days compared to 100 days in the open ocean based on the Desaubies formulation (*Desaubies*, 1976) of the Garrett–Munk (GM) internal wave spectra (*Garrett and Munk*, 1972, 1975)], implying the internal wave field in the Arctic Ocean cannot reach typical saturated GM internal wave energy levels.

Acoustic Doppler Current Profiler (ADCP) observations in the Canada Basin (*Pinkel*, 2005) suggest that most near-inertial internal waves in the Arctic exist in a one-bounce scenario, i.e., that they are generated at the surface, reflect once off the bottom and then dissipate in the under-ice boundary layer (*Morison et al.*, 1985). Despite historic declines in sea ice thickness, extent, and concentration in the Pacific sector of the Arctic Ocean in the past 10 years, a number of observational studies suggest that Arctic Ocean internal wave energy is still low, and it remains unclear how this might change in the future. Internal wave energy levels and inferred mixing measured in the last 10 years with Expendable Current Profilers (XCP) compared with similar observations from the 1980s show little change in internal wave energy and mixing (*Guthrie et al.*, 2013). Strong near-surface stratification associated with the accumulation of fresh water appear to continue to enhance the dissipation of internal wave energy in the under-ice boundary layer (*Guthrie et al.*, 2013).

Changes to near-surface stratification on weekly to monthly timescales clearly alter the internal wave field (*Cole et al*., 2014). Comparisons of internal wave shear measured at identical locations in the Beaufort Sea by the ONR Seasonal Ice Zone Reconnaissance Surveys project show virtually no difference between ice-free and ice-covered conditions, with inferred mixing values consistently $O(10^{-6})$ $m^2\ s^{-1}$. However, internal wave vertical displacement estimates from Canada Basin Ice-Tethered Profiler (ITP) data (*Dosser and Rainville*, 2015) show a seasonal cycle in near-inertial internal waves that is related to both wind strength and ice characteristics. While the 10-year (2005–2014) time series of ITP estimates shows only a minor increasing trend in mean amplitude, the distribution of internal wave amplitude may be changing.

Measurements of mixing under arctic storms (*Kawaguchi et al*., 2015), and with better time and space resolution (e.g., MIZ and Sea State of the Emerging Arctic Ocean DRIs data), are emerging, which may lead to a better understanding of the integrated impact of internal waves and episodic processes driven by patchy air–ice–ocean fluxes. Unfortunately, it is difficult to capture the fate of near-inertial internal waves in the Arctic Ocean from generation to dissipation, because in the presence of ice cover, concurrent high-resolution fixed point measurements of wind speed, ice drift, and ocean velocities from the surface to depth are difficult to make.

3. Science Objectives

SODA focuses on understanding how the upper Beaufort Sea responds to changes in inflow and surface forcing. Specific science questions address three oceanographic properties: buoyancy, momentum, and heat.

Buoyancy. What are the causes and consequences of the changing upper ocean stratification (mixed layer and Pacific Water)?

- *Vertical*: What is the interplay among wind entrainment, convection, solar heating, and buoyancy input?
  - On synoptic, seasonal, and year-long integral timescales?
  - How does this balance vary with sea ice conditions?
- *Lateral*: What is the importance of heterogeneity in mesoscale and submesocale processes?
  - On synoptic, seasonal, or year-long integral timescales?
  - How spatially variable is this balance? (Is it more important at some locations, e.g., ice edge, mesoscale fronts, etc.?)

Momentum. How is the wind stress partitioned within the ice–ocean system? (depth and frequency; surface waves; ice motions; mixed layer and deeper acceleration; internal waves)

- How do sea ice properties affect this partition?
- How do the buoyancy flux and stratification affect the partition?
- How do lateral contrasts in forcing or ocean structure affect the partition and create secondary circulations?
- How does the phenology of the air–ice–ocean system affect the partition?

Heat. What is the fate and impact of the significant increase in upper ocean heat (and the associated sound channel)?

- What processes control the near surface temperature maximum formation and release?
  - How does it impact the fall sea ice freeze-up?
  - How does it vary with sea ice conditions?
- How difficult is it for the mixed layer to entrain and access heat carried in the Pacific Water, and how does it vary with sea ice conditions?

4. Experiment Strategy

SODA science objectives guide the design of a measurement strategy to:

- Capture upper ocean responses to atmospheric forcing over a large range of ice conditions and forcing characteristics by sampling across a broad spatial extent through a complete annual cycle.
- Resolve the upper ocean and key sea ice properties, and as much as possible local atmospheric forcing.
- Characterize the temporal evolution of the vertical and horizontal structure of the ocean stratification and heat content.

The SODA measurement program builds on advances in autonomous observing from the Marginal Ice Zone DRI to employ a system consisting of four interrelated components (Figure 6): (i) drifting observations from ice-based buoys and instruments drifting in the water column, (ii) geographically fixed sampling by moorings and gliders, (iii) Beaufort Sea inflow observations by floats and Pressure Inverted Echo Sounders (PIES), and (iv) a ship-based process study, all of which will be augmented by remote sensing and numerical simulations. Together, these complementary elements will sample through diverse atmospheric forcing and ice cover regimes, providing a wide dynamic range to address the SODA science questions.

Moorings and autonomous ice-based and mobile oceanographic platforms provide year-round access to regions of both full and partial ice cover. Clusters of ice-based buoys provide persistent, collocated sampling of the atmosphere–ice–ocean system, including meteorological variables, sea ice properties, and temperature, salinity, velocity and turbulence in the upper ocean and pycnocline. Moorings collect high-resolution time series of upper ocean variability and sea ice draft over an annual cycle, and provide acoustic geolocation for autonomous platforms. Gliders conduct repeat surveys around the mooring array. Together, moorings and gliders provide 3D time series of upper ocean and pycnocline variability, across a range of ice conditions, and over a complete annual cycle.

PIES arrays monitor inflow regions. Profiling floats provide distributed sampling while following inflow to the Beaufort Sea and drifting within the region occupied by the moorings. Ship-based high-resolution synoptic surveys and turbulence measurements will be used to investigate summertime mesoscale and submesocale processes from the open water to the ice edge. Opportunistic sampling of currents and turbulence on the basin scale provides broader context in summer. Remote sensing provides critical data on ice cover, and numerical studies will support experiment planning and subsequent interpretation of the observations.

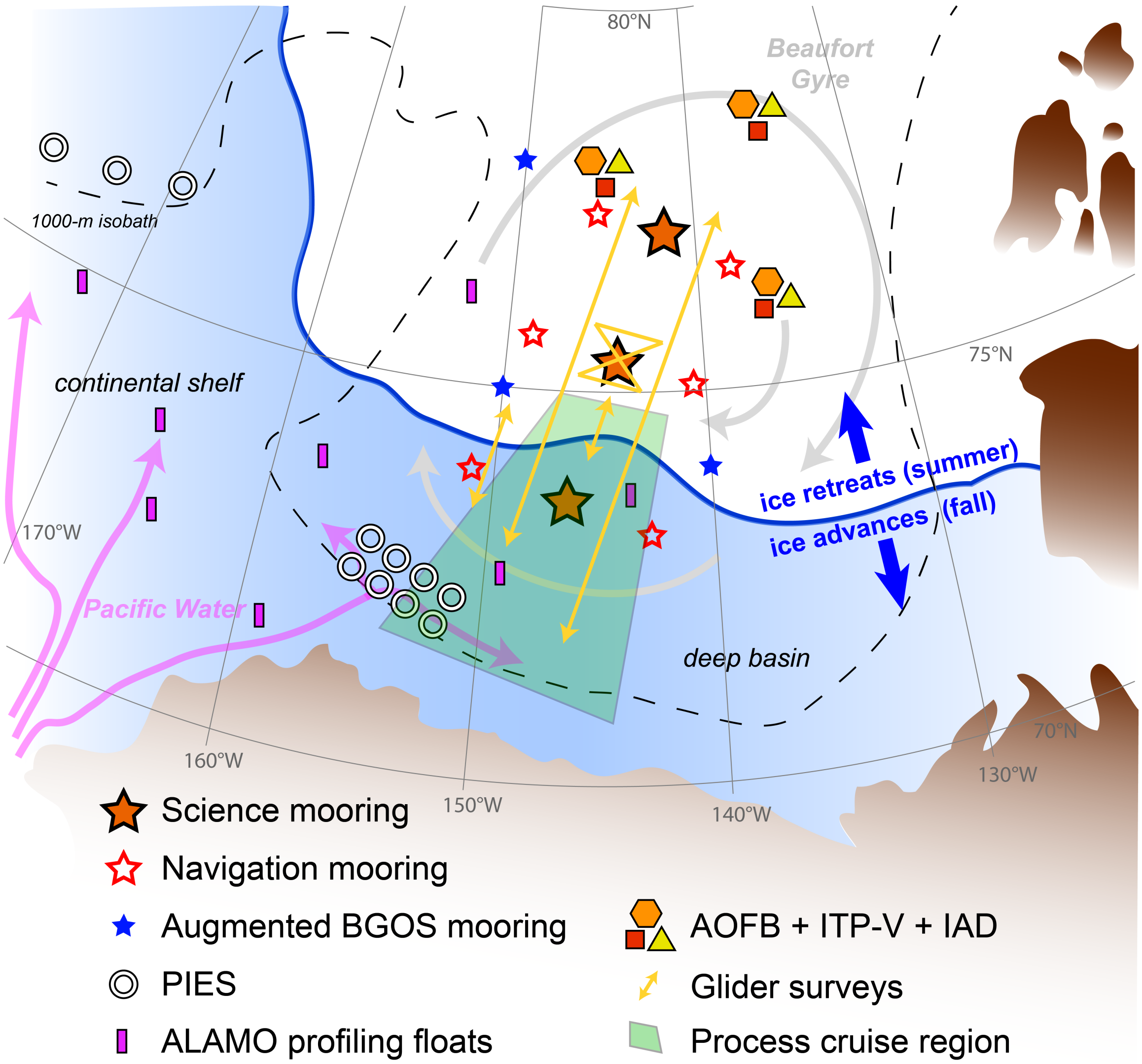

Figure 6. Schematic representation of the SODA observing plan. BGOS, Beaufort Gyre Observing System; PIES, Pressure Inverted Echo Sounder; ALAMO, Air-Launched Autonomous Micro Observer; AOFB, Autonomous Ocean Flux Buoy; ITP-V, Ice Tethered Profiler with Velocity; IAD, Integrated Autonomous Drifter.

Coordination between geographically fixed and drifting instruments, and between platforms sampling within the ice and those working in open water, presents challenges for the experiment design. The overarching strategy balances the desire to capitalize on the particular strengths of each of the approaches while also aiming to maximize integration through coordinated, collocated sampling. The deployment strategy for the ice-based buoy clusters has been guided by the desire that these drifting assets sample around the bottom-anchored moorings and glider survey region for at least part of the measurement period, under the constraints of the seasonal variation in sea ice extent and the pattern of ice drift. Ideally, clusters will be deployed on robust multiyear ice floes that will both remain intact during the study and drift past the moorings at some point during their operational lifetime. But it is likely that at best, each drifting buoy cluster will be near the moorings for only a limited period of time.

Similarly, ship-based surveys will sample a relatively brief period during the first summer of the field program. For the process study, the ship will be unable to access the ice-covered regions where many of the other assets operate, but it can coordinate with those platforms to complement measurements collected in ice-covered regions with exceptional sampling near the ice edge.

The experiment design attempts to maximize opportunities for joint sampling by the three components while also configuring each to be self-contained, such that each component can address SODA science questions independent of collocation with the others. Joint analysis of the combined data sets will offer the greatest dynamic range and, when components are collocated, the most complete sampling of the atmosphere-ice-ocean system, but significant information will also be obtained when the components sample in isolation.

4.1 Observational approach

4.1.1 Ice-based observatory program

The specific goals of the SODA drifting buoy program are to acquire multi-season observations of the interactions among elements of the air–ice–ocean boundary layer system and document their effects on generating and destroying upper ocean stratification. These ocean–ice interactions directly force the formation and destruction of both weak summer stratification and trapped heat layers within the seasonal ocean mixed layer, and entrainment of main halocline waters. A mix of technologies, co-located on the same ice floes, will be used (with redundancies to better insure information return): Enhanced Autonomous Ocean Flux Buoys (AOFBs), Integrated Autonomous Drifters (IADs), and Ice-Tethered Profilers with Velocity (ITP-Vs). Each platform is moored into and drifts with the ice (Figure 6; hexagons, triangles, and squares), and can be deployed within a few 10s of meters on the same ice floe.

Autonomous Ocean Flux Buoys. Enhanced AOFBs will be developed and deployed to make measurements of turbulent heat, salt, and momentum fluxes just below the ocean–ice interface as well as observations over a 6-m layer within the seasonal pycnocline of turbulent diffusivity and inferred heat fluxes. Also in the ocean, high temporal resolution ocean velocity and temperature profile information will be acquired with Acoustic Doppler Current Profilers and temperature chains interfaced to the AOFBs. Topside, the systems will support wind, air temperature, and short-wave insolation sensors, and high-resolution GPS-based ice velocity measurements.

Integrated Autonomous Drifters. IADs will incorporate meteorological sensors, a high-resolution (2-cm spacing) temperature string to estimate ice thickness and associated properties (effectively an integrated Ice Mass Balance buoy), and a second temperature string extending to 200 m at 25-cm to 2-m spacing (optimized for the expected pycnocline depths) to provide high-frequency, high-resolution upper ocean structure. The drifters will also make surface wave measurements (using a sensitive attitude and heading reference system) and will provide frequent GPS position information to derive ice dynamics (differential kinematic parameters, clockwise inertial velocities, etc.).

Ice Tethered Profilers. ITP-Vs will collect profiles of ocean temperature, salinity, and velocity at 1-m vertical resolution. These profiles will be obtained nominally at a 3-hr interval from ~7 to ~250 m depth, with occasional sampling to 750 m. Between profile operations, turbulent heat, salt, and momentum flux measurements will be made (nominally 4 m below the ice–ocean interface). The ITP-V sampling pattern is flexible and can be modified in near-real time, allowing enhanced sampling to occur during storms, for example. The ITP-V systems will also acquire high temporal resolution temperature and salinity measurements at two fixed depths just below the ice–ocean interface to document the development of melt water lenses in summer.

Deployment Strategy

Most of the ice-based drifting instruments will be ice-breaker deployed in the Beaufort Sea in fall 2018 on at least three ice floes distributed in the northeastern Canada Basin at locations chosen to maximize the likelihood that they (1) survive fall freeze-up and (2) drift over the moored SODA instruments. This strategy is designed to provide concurrent sampling of the upper ocean system across a drifting swath, quantifying the heterogeneity of the upper ocean stratification and heat distribution and the resulting vertical fluxes. In addition, one instrument cluster with an ITP-V, AOFB, and Ice-Mass Balance Buoy is planned to be deployed in the Siberian Sea in conjunction with the 2017 Nansen and Amundsen Basins Observation System expedition to sample contrasting upper ocean conditions as this cluster crosses the North Pole in the Transpolar Drift. All the drifting instrument systems will sample periodically multiple times each day, and report their data via Iridium satellite link, allowing first look data to be reported in near-real time.

Science Questions and Anticipated Outcomes

The drifting buoy program in SODA will focus on several research questions relating to how forcing of the ice–ocean system impacts the evolving upper ocean stratification of the Arctic. Specific questions include:

- How do differences in sea ice properties, including strength, mobility, open water fraction, and bottom roughness, impact the transfer of momentum from atmosphere to ocean?

- How do the exchanges of heat between air and ice and between ice and ocean vary seasonally and spatially over the Arctic, and how do the associated changes in ice volume manifest as changes in the upper ocean thermohaline stratification (including mixed layer thickness)?
- What combinations of atmospheric forcing, ice properties, and mixed layer characteristics allow for efficient internal wave generation and propagation in the stratified waters below? What role do these internal waves have in supporting mixing within the arctic pycnocline? What are the consequences and feedbacks between mixing in the pycnocline and the air–ice–ocean boundary layer system?

Each drifting instrument cluster will quantify properties of the atmosphere, ice, ocean mixed layer, and ocean pycnocline. Data from surface instruments — vector wind, temperature, and short-wave insolation sensors — will yield estimates of surface stress and shortwave radiative fluxes. Ice motion and deformation will be quantified with high-resolution GPS position data. Ice and upper ocean thermal structure will be measured by a hierarchy of temperature sensors; 2-cm vertical spacing in the ice will provide estimates of ice thermal conductivity and thickness, while longer temperature chains with 15-cm vertical resolution will extend through the upper water column to resolve the heat content of stratified layers associated with weak pynoclines that form during the high insolation summer months.

The AOFB upper ADCP and eddy correlation flux packages suspended 2.5 m below the ice will measure vertical turbulent fluxes of heat, salt, and momentum that will be integrated with comparable flux measurements made by the ITP-Vs 4 m below the ice. The resulting heat and salt flux estimates will be compared with direct local basal ice melt and growth observations inferred from the thermistor strings and a 1-cm-resolution coherent altimeter. Mixed layer currents and ice–ocean shear will be observed by the AOFB ADCP at 15-min resolution and by the ITP-V at ~2-hr resolution (by combining profile and flux period observations). Combining the ADCP and ITP-V shear measurements with the ITP T–S and density structure profiles will allow the shear stability of the surface layer to be assessed through calculation of the gradient and bulk Richardson numbers.

The long temperature strings, the AOFB ADCP and pycnocline frame, and the ITP-V will sample the stratified waters below the surface mixed layer. These data will be used to characterize the internal wave properties and associated turbulent mixing. The ADCP will measure ocean velocity through the upper 65–80 m (depending on acoustic backscatter conditions) at 2-m and 15-min resolution, while the ITP-V will return 1-m-resolution temperature, salinity, and velocity data at a 3-hr period. The long temperature strings will document vertical isotherm displacements at 2-min resolution. All of these observations will be used to quantify momentum transfer to the ocean as well as the internal wave characteristics as a function of time and space during the buoy cluster drifts.

The AOFB pycnocline frame suspended 45 m below the flux packages will measure finescale and microscale thermal gradients allowing estimation of the turbulent thermal diffusivity within the warm Pacific Summer Water (PSW) layer found in the Beaufort Sea. These concurrent mechanical forcing and diffusivity measurements will be used to identify the physical processes (including internal wave instability mechanisms) that force the highly intermittent vertical fluxes within this strongly stratified part of the arctic water column.

Analysis of the SODA ice-based observatory data, in combination with results from the bottom-anchored program, will advance understanding of the time-varying air–ice–ocean boundary layer system and its influences on the Arctic's upper ocean stratification.

4.1.2 Geographically fixed sampling

A system of moorings (Figure 6; orange and blue stars) and autonomous gliders (Figure 6; yellow lines) will maintain both the regional focus and year-long persistence to capture the desired range of ice, ocean, and atmospheric conditions, while also providing the high-resolution measurements required for process investigations. A system of moorings distributed latitudinally and gliders will sample the central Beaufort Sea, focusing on upper ocean responses to atmospheric forcing and the impact of variable ice cover away from the complicating influence of the boundary. Additionally, existing National Science Foundation Arctic Observing Network moorings, situated east of the Northwind Ridge, will be augmented to resolve near-inertial motions in the upper ocean. Geographically fixed sampling elements include moorings, gliders, and an acoustic navigation array.

Moorings. Three bottom-anchored, sub-surface moorings, distributed latitudinally between 74°N and 78°N, will collect rapidly sampled (resolving internal waves), high vertical resolution measurements of velocity, temperature, and salinity in the upper 200 m, with more coarsely spaced measurements extending to the core of the Atlantic Water layer, around 500-m depth. The moorings also collect high-resolution acoustic measurements of three-dimensional ice bottom roughness and draft, as well as ice velocity and surface waves (in open water) using new multibeam sonars from Nortek Signatures. Additionally, Beaufort Gyre Exploration Project moorings BGOS-A and BGOS-B will be augmented with McLane Moored Profilers. The two BGOS moorings will provide measurements near the Northwind Ridge, with considerable latitudinal distribution. Existing deployments of Nortek Acoustic Wave and Current Profilers on BGOS-A and BGOS-D will also be continued as part of SODA.

Gliders. Seagliders will occupy high-resolution sections centered on the three central Beaufort moorings, resolving variability in temperature, salinity, optics, and turbulence at short spatial scales for the duration of the experiment. Rapidly repeated sections near the moorings complement the highly resolved mooring time series to provide four-dimensional sampling of the upper ocean. Longer sections running between the moorings and beyond provide large-scale spatial context that will be important for upscaling the detailed understanding developed at the intensively sample sites toward results that can be used to evaluate regional models. Early in the mission gliders will also conduct surveys designed to inform and augment the ship-based process studies. Gliders will operate for an entire year, with completely autonomous operations for the roughly nine-month period of full ice cover.

Acoustic navigation array. Acoustic navigation beacons mounted on each of the three science moorings, augmented by at least four additional bottom-anchored navigation moorings, will provide geolocation required for autonomous platforms operating under sea ice in the central Canada Basin. The array will exploit the sound channel created by the PSW to ensonify a large (many hundreds of kilometers) region around the mooring array. The system will employ a variant of the mid-frequency source use in the MIZ DRI, operating at a lower frequency and higher output level to maximize range, and thus the overall coverage.

Deployment Strategy

Central Beaufort science moorings will be deployed in late summer 2018 and recovered in summer 2019. Given atmospheric systems with scales of a few hundred kilometers, latitudinal position and separation between moorings will be balanced to sample a range of sea ice conditions that sometimes experience forcing by the same atmospheric event. Nominal positions are 74°N, 75°N, and 78°N. To maximize access to the northern sites, which may remain ice covered in summer, SODA will request icebreaker support (e.g., USCGC *Healy*) for the summer 2018 deployment. This cruise will also be used to deploy ice-based assets and PIES. The icebreaker will be essential to maximize the chance of success during the 2019 recovery. SODA instruments will be added to the BGOS moorings as part of their regularly scheduled service cruise.

Seagliders will begin operations in summer 2018, deployed from R/V *Ukpik* off the Alaska coast following the operational scheme used in the MIZ DRI. Initial surveys will collect sections near the ice edge, spanning open water, marginal ice zone, and pack to inform the ship-based surveys and provide complementary measurements in regions that cannot be accessed by the ship. The 2018 mooring deployment cruise will recover this first flight of gliders and replace them with a group of vehicles that will repeatedly occupy sections in the region surrounding the Central Beaufort mooring array for the entire annual cycle. Gliders will be recovered as part of the summer 2019 mooring recovery cruise, with the northernmost vehicles transiting south to open water, should their patrol areas be ice-covered near recovery time.

Provided that cost-efficient logistics can be identified [e.g., joining the Canada Basin Acoustic Propagation Experiment (CANAPE) recovery cruise or the annual IBRV *Araon* cruise], the SODA navigation array will be deployed in summer 2017, equipped with enough batteries to operate for three years. Deploying the navigation array a year ahead of the intensive field season provides operational flexibility, allowing gliders to begin sampling in advance of the 2018 process and mooring deployment cruises such that they can be used to guide and augment the ship-based surveys. The added year of energy would allow the navigation network to remain in place to support continued float and glider operations and future programs, such as the Arctic Mobile Observing System

Department Research Initiative. Alternatively, the navigation array could be deployed with the Central Beaufort moorings in summer 2018.

Science Questions and Anticipated Outcomes

The system of moorings and gliders, sited in the basin interior where sea ice undergoes large seasonal transitions, is designed to quantify how atmosphere–ice–ocean interactions govern upper ocean evolution.

- What processes set the vertical and horizontal structure of upper ocean stratification, and how do these evolve with changing ice conditions?
- How do horizontal structures of density and velocity vary on scales from roughly 1 to 400 km over the seasonal cycle?
- How do atmospheric forcing, diverse ice conditions, and existing vertical and lateral stratification interact to govern mixed layer deepening (entrainment) and shoaling (restratification).
- What combinations of atmospheric forcing, ice properties, and mixed layer characteristics allow efficient internal wave generation and propagation?
- What mix of ice properties (including under-ice roughness), upper ocean structure (stratification and velocity), and wave characteristics result in efficient under-ice dissipation of upward propagating internal waves?

Both Central Beaufort and BGOS moorings define a fixed frame of reference and provide high vertical resolution time series of ocean stratification and velocity extending from near the ice–ocean interface to the pycnocline. Moored instruments will sample rapidly to resolve most of the internal wave band (from near the 6-cycle hr^{-1} buoyancy frequency through the inertial) and quantify variability at longer time scales. Multibeam sonar (SODA-A, B, C), and upward looking sonar (BGOS-A, B), and ADCPs will measure ice draft and velocity, with additional data on the spectra of bottom roughness from the swath measurements produced by the multibeam. These measurements will inform investigations into how varying sea ice mobility, open water fraction, and bottom roughness impact the transfer of momentum from atmosphere to ocean and how this partitions into mixed layer advection, entrainment, and internal wave generation.

Gliders will survey continuously near the moorings, providing estimates of horizontal gradients in temperature and salinity. During summer and fall, when regions of open water are present, a subset of gliders will survey across the marginal ice zone, capturing the dramatic variations in atmospheric forcing (heat, momentum) and corresponding oceanic heterogeneity associated with the transition from open water to pack ice. When the ocean is nearly entirely ice-covered and surfacing is not possible, gliders will conduct focused, small-scale patterns near the moorings and longer sections that span the array. Measurements collected by glider surveys will be used to estimate horizontal coherence and spectra of lateral structure, and to produce time series maps of variables that include stratification, mixed layer depth, spice (a diagnostic for lateral stirring), and diapycnal mixing.

4.1.3 Beaufort Sea inflow observations

A combination of PIES and profiling floats will investigate inflow pathways from the Pacific. Measurements from two PIES arrays will be used to investigate how eddies over the Chukchi Shelf and at the mouth of Barrow Canyon contribute to heat transport into the Canada Basin, as well as the internal wave environment at depth on the Chukchi Shelf and in the Canada Basin. Complementing these fixed measurements, profiling floats will be deployed to document the paths followed by inflowing Pacific waters as they leave the Chukchi Shelf and to understand the processes that modify the inflowing water masses as they traverse the basin.

Deployment Strategy

Profiling autonomous (Air-Launched Autonomous Micro Observer, ALAMO) floats will measure the seasonal evolution of the ocean temperature and salinity stratification as well as the horizontal circulation of the warm PSW as it moves from the Alaska and Chukchi shelves over the Chukchi Borderland and Plateau and into the Beaufort Gyre. Fifteen floats will be deployed on the eastern edge of the Chukchi Borderland in water less than 1000 m. Three of them will act as virtual moorings by sitting on the bottom and profiling up to the surface then going back to parking on the bottom. The other 12 will sit on the bottom and at intervals begin a mission parking at some shallower depth to provide an understanding of the Langrangian pathways of the PSW entering the Canada Basin from the Chukchi Sea over time. In this scheme, the group of floats are deployed, each with an anchor system that secures them to the site. Then, at programmed intervals, a subset of the floats will release their anchors and begin their profiling mission. The other 15 floats will be deployed by ships of opportunity in the Beaufort Gyre to fill out the sampling of the circulation. The handful of these floats deployed on the Chukchi Shelf will provide a broader view of how the PSW moves off the shelf and over the Chukchi Borderland and Plateau regions. Knowing where and when such exchanges occur will provide insight to the dynamics behind the warming Pacific Water of the Beaufort Gyre.

PIES arrays will characterize the passage of warm and cold core eddies across inflow pathways to the Beaufort Sea. Five Rapid PIES and three Rapid Pop-up Data Shuttle Current PIES (PDS CPIES) will be arranged in a grid at the mouth of Barrow Canyon, spaced at 40 km, and in the vicinity of the 1000 m to 2000 m isobaths. These eight instruments will be deployed from the USCGC *Healy* or R/V *Sikuliaq* in 2018 for one year to monitor filaments and eddies of warm PSW as they enter the deep basin from Barrow Canyon. The high temporal resolution measurements of acoustic travel time will be used to infer small-scale variability in eddy structure. As part of the CPIES, Aanderaa current meters moored 50 m above the bottom will make point near-bottom velocity measurements, which will provide estimates of inertial and sub-inertial velocities near the bottom. These measurements will provide an estimate of the near-bottom internal wave activity.

Three additional PDS CPIES will be deployed in the northern Chukchi Sea to augment the Korean Polar Research Institute moored array. These will be deployed and recovered from the IBRV *Araon* in fall 2017, and will provide a long, multi-year time series of near-bottom kinetic energy and vertically integrated oceanic heat content in the Chukchi Sea.

Science Questions and Anticipated Outcomes

The PIES array addresses questions relating to the advective heat flux associated with Barrow Canyon eddies and the propagation of near inertial wave energy to the seabed.

- Long time series of the vertically integrated heat content from the PIES, along with the trajectories and water mass transformation estimates from the ALAMO floats will provide insight into the circulation and renewal rate of the PSW.
- Vertical acoustic travel time measurements enable long-term monitoring of warm Pacific Water eddies, providing information on the temporal variability in this heat flux from the Bering Strait. Additionally, these measurements will provide indications of changes in the temperature or vertical size of the eddies, and any long-term trends in the heat content of the overlying water during the course of the deployment.
- Near-bottom currents from the PDS CPIES will quantify the amount and variability of near inertial wave energy that reaches the seabed both at the southern boundary of the Canada Basin and in the Chukchi Sea.

Near-bottom currents from the PDS CPIES will quantify the flux of near-inertial wave energy that reaches the seabed both in the Canada Basin and in the Chukchi Sea, and provide information on the internal wave environment throughout the deployment at both locations. Concurrent measurements of the presence or absence of sea ice above can be used to assess the influence of sea ice on near-bottom currents.

4.1.4 Ship-based process study

A 21-day summertime process cruise using R/V *Sikuliaq* will conduct high-resolution synoptic surveys and turbulence measurements aimed at resolving the rapidly evolving, small-scale dynamics that govern the upper ocean near the ice edge (Figure 6; green shaded region). Adaptive, process-resolving measurements complement the sustained measurements collected by SODA’s drifting and geographically fixed elements. Ship-based surveys will be guided by the fact that most of those processes involve small lateral and or vertical scale features and motions, often evolve rapidly in time, and are frequently enhanced near particular features (e.g., meltwater fronts, the ice edge) that themselves move in space and evolve in time. Incoming data from satellite remote sensing, autonomous platforms, and the synoptic survey tools themselves allow adaptive decision making to target the most salient features and scales to sample. Synoptic surveys will integrate multiple high-resolution instruments to collect concurrent measurements as a single platform.

Modular Microstructure Profiler (MMP). This tethered profiler makes high-resolution estimates of both shear and temperature microstructure, profiling to 300 m in 15 min, or shallower depth ranges more rapidly.

Shallow Water Integrate Mapping System (SWIMS). This winched towed body has a CTD, upward and downward looking ADCPs, and a "χ-ometer" temperature microstructure sensor. It makes tight saw-tooth patterns (e.g., 400-m horizontal spacing for profiles to 100-m depth at 5 kn, or tighter at slower speeds).

3D Sonic Anemometer. This will measure wind stress directly from the foremast of the ship.

SWIFTs. These freely drifting buoys measure winds, waves, salinity, temperature, and turbulence in a surface following reference frame. Arrays of these are deployed to understand spatial variability. Deployments span hours to days.

Deployment Strategy

Towed profiling and microstructure profiling operations, especially when conducted near the ice edge, require a vessel capable of precise maneuvering at speeds of 1–8 kn. Scientific goals also dictate underway instrumentation that includes shipboard ADCPs and science-quality meteorological packages. The SODA process cruise will use R/V *Sikuliaq*, which meets the program seakeeping and scientific requirements.

Process cruise objectives are best served by fieldwork in late summer (September), as this allows an optimization between maximum open water extent, and thus the widest possible access for R/V *Sikuliaq*, and increasing likelihood of wind events moving into late September. Surveys will take place in the Central Beaufort, with specific sites determined adaptively to target key features and leverage SODA moored, drifting, and gliding assets. Operations will span open water and substantial slush to study variations of surface forcing on ocean response.

Should timing and cruise plans allow, process cruise surveys will be coordinated with the augmented BGOS CTD, LADCP, and microstructure sampling. Synoptic surveys could be conducted around BGOS stations if longer survey lines could be occupied perpendicular to the BGOS track to provide a more three-dimensional snapshot.

Science Questions and Anticipated Outcomes

Process cruise surveys will focus on:

- Quantifying the turbulent processes that transfer heat and momentum towards and away from the ocean–atmosphere interface using concurrent high-quality measurements of both atmospheric heat and momentum fluxes above the air–sea interface and turbulent fluxes of heat and momentum through the upper ocean.
- Disentangling the balance between 1D and advective processes. A combination of time series in chosen locations and small adaptive surveys around such location

will allow attribution of observed changes in upper ocean heat, freshwater, and momentum content to divergences and convergences of the vertical turbulent fluxes and to advection of local small-scale gradients. This will bound the role and relevance of 1D models of turbulent mixing in open water and slush, and constrain the relative importance of different underlying processes (e.g., Ekman processes, wind-driven turbulence, Langmuir turbulence, sub-mesoscale re-stratification, near-inertial shear, and internal wave generation and breaking).

- Understanding the evolution of sub-surface pockets of heat, e.g., PSW. Long (100 km), high-resolution sections will attempt to document the dissipation of pockets of PSW to estimate the distance over which they may transport heat. These measurements will complement those collected by other SODA assets by assessing whether breakdown of PSW is driven by small-scale processes that are not resolved by autonomous sampling.
- Quantifying deformation as a diagnostic for small-scale dynamics. The combination of the ship measurements and the SWIFT drifters can quantify truly synoptic lateral gradients in the upper ocean. Such strain rates can play a key role in identifying different underlying dynamics. For example, synoptic vorticity measurements differentiate well small-scale, near-inertial motions from sub-mesoscale instabilities and vortices, both of which may be active in the upper Arctic Ocean.
- Augmenting observations collected by moored and mobile assets. Within the constraints of deployment timing and ice cover, process cruise sampling will include small- and medium-scale surveys near other accessible SODA assets (gliders, moorings, drifters). These will resolve what observed variability is due to intrinsic temporal changes versus effects of local spatial gradients.

4.1.5 Ship-based vertical mixing observations

A second ship-based effort will take advantage of basin wide cruises of opportunity on the CCGS *Louis St. Laurent* in late summers 2017 and 2018. These cruises will make lowered ADCP and microstructure (temperature and shear) measurements at 30–40 CTD stations distributed throughout the Canada Basin. Full depth casts will be taken, with the expectation that data will be of good quality in only the upper portion of the water column due to weak signals and low backscatter levels at depth.

Science Questions and Anticipated Outcomes

The objectives of this component are similar to those related to the internal wave segments of the drifting and moored components. These observations will address those objectives while providing a broad spatial context for SODA observations and a look at year-to-year variability.

4.1.6 Modeling

A three-dimensional linear near-inertial wave model following the modal decomposition formalism of *Gill* (1984) and *Zervakis and Levine* (1995) (ZL95) will be developed as part of the SODA DRI. The model will be used to assess the importance of near-inertial internal wave field parameters like mixed layer depth, stratification, storm size, direction of storm propagation, and the latitudinal variation of the Coriolis frequency (β). Besides the presence of sea ice, there are two defining differences in the Arctic Ocean environment and two more subtle factors that may reduce the surface forcing of near-inertial internal waves. By applying the ZL95 model and using standard hydrographic profiles and storm direction and size, we will be able to model the magnitude and propagation of near-inertial currents in the pycnocline.

Based on previous results, we have identified four significant differences between the Chukchi and Beaufort seas and mid-latitude oceans that could severely impact the strength of the internal wave field in the Arctic Ocean even in the absence of perennial sea ice cover: relatively small β, shallow summer mixed layer depth, and storm direction and extent. The ZL95 model will enable us to quantify these effects on Arctic near-inertial internal wave energy. Application of the model will allow the disentanglement of these parameters, enabling a number of sensitivity experiments focused on exploring the differences between the Beaufort Sea and mid-latitude near-inertial internal wave fields for similar forcing or in the absence of sea ice.

Prior to the onset of the field campaign, previous Arctic Ocean data sets particularly applicable to the SODA DRI will be leveraged to initialize the model and compare model output to observations.

Science Questions and Anticipated Outcomes

The modeling effort will focus on the following:

- What role do hydrographic differences between the Arctic and lower latitude oceans have in generating near-inertial internal waves in the Beaufort Sea?
- In the presence of relatively small β (1/3rd the value at 75°N compared to 45°N), what other factors are important in introducing the small-scale fluid convergences and divergences that drive inertial pumping at the base of the mixed layer thought to be responsible for creating near-inertial waves?
- Do relatively shallow summer mixed layer depths more evenly distribute the available horizontal kinetic energy into higher modes? Previous studies have shown that deeper mixed layers result in a larger percentage of available energy contained in the first few modes. This could have a profound impact on lateral energy fluxes in the Arctic Ocean.
- How important are storm direction and size in near-inertial internal wave generation in the Arctic Ocean?

4.2 Timing and logistics

The SODA observational program's primary operational objectives are:

- Deploy acoustic navigation moorings (Central Beaufort)
- Deploy PIES (Northwind Ridge and Barrow Canyon)
- Augment BGOS moorings and surveys (Central Beaufort)
- Deploy ALAMO floats (Chukchi Shelf and Beaufort Sea)
- Deploy ice-based clusters (Central Beaufort)
- Deploy SODA moorings (Central Beaufort)
- Deploy Seagliders (Beaufort Sea)
- Embark on process cruise (Central Beaufort)
- Recover moorings, autonomous platforms (Central Beaufort)

SODA will address these needs using a mix of dedicated cruises aboard R/V *Ukpik*, R/V *Sikuliaq*, and USCGC *Healy* and, provided that opportunities are available, collaborative operations from CCGS *Louis St. Laurent*, IBRV *Araon*, and USCG C-130 Arctic Domain Awareness flights. Figure 7 provides a timeline of operations and sampling periods.

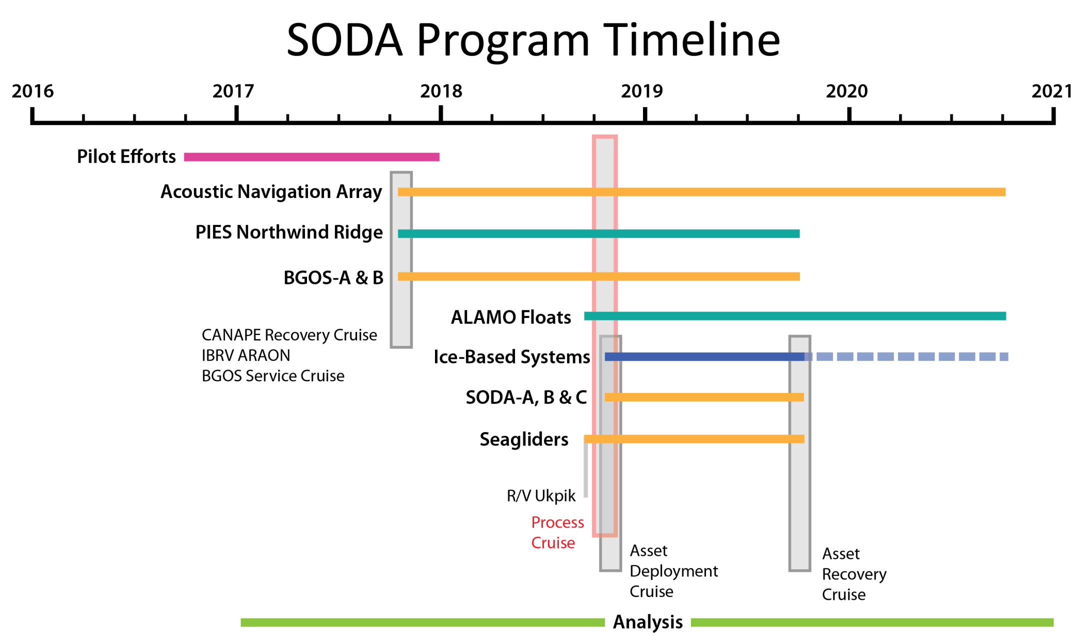

Figure 7. SODA observing activities. Blue lines mark ice-based observing, gold geographically fixed measurements, green inflow observations, and red-outlined box the process cruise. Other grey boxes mark cruises.

Ideally, operations will begin with the summer 2017 deployment of the SODA acoustic navigation array, undertaken in conjunction with the CANAPE recovery cruise and augmentation of the BGOS moorings, during the annual service cruise aboard CCGS

Louis St. Laurent. A 2017 navigation array deployment will support gliders operating concurrently with the process cruise, prior to the deployment of the other SODA moorings. At roughly the same time, an array of three PIES will be installed in the northern Chukchi Sea as part of a collaboration between SODA and the Korean Polar Research Institute's annual efforts in the Arctic.

ALAMO float and glider deployments will begin as soon as there is sufficient open water in summer 2018, with the goal of having assets in place and sampling to support the late summer process cruise. Floats will be deployed using a combination of ships of opportunity and USCG C-130 flights. Gliders will be deployed over the Alaska slope from the small R/V *Ukpik*, mirroring the deployment scheme used in the MIZ and CANAPE programs.

R/V *Sikuliaq* will begin intensive process surveys in late summer 2018, timed to maximize access to open water while still sampling late enough in the year to capture strong wind events.

USCGC *Healy* will follow shortly afterward, to deploy a PIES array off Barrow Canyon, the SODA-A, B, and C moorings, and the ice-based clusters. Timing for this operation is critical, as survivability of ice-based assets depends strongly on being able to select strong ice floes that are likely to remain intact until they are refrozen into the pack. Such floes can be more reliably identified at the end of the melt period in late September, as the sea ice begins to form again (Figure 5). Additionally, this timing supports deployment of ice-based clusters far to the north, where preliminary studies suggest that the ice drift may carry them into the region occupied by the moorings (Figure 6). Provided that the cruise does not extend too far into freeze-up, mooring operations should not be impeded by ice cover and weather. The *Healy* cruise will also deploy fresh Seagliders to maintain sampling through the winter.

Moorings will be recovered by USCGC *Healy*, or a vessel with similar capabilities, in late summer 2019. Recovery of autonomous assets will depend on the balance of cost vs. benefit. Priority will be given to instruments carrying data that have not been previously uploaded via satellite communications and instruments that are within easy reach of the cruise track or mooring recovery region. SODA autonomous platforms should pass all of their data back to shore whenever satellite communication is available (i.e., when they have access to open water). Thus, under normal circumstances, the instruments themselves could be considered expendable.

5. Resources and Program Components

Measurement assets available to the SODA program include:

Moored

- (11) Pressure Inverted Echo Sounders with deep current meters.
- (3) Moorings (SODA-A, B, and C), each instrumented for: (i) high-resolution measurements of T, S, and **u** from the ice–ocean interface or surface to 200-m depth, with coarser measurements below, (ii) swath measurements of ice draft using a multibeam sonar, and (iii) surface waves using Nortek Signature Doppler profilers. Moorings also carry acoustic navigation sources.
- (4–6) Moorings to provide an acoustic geolocation network.
- (2) McLane Moored Profilers to augment Beaufort Gyre Exploration Project moorings (BGOS-A, BGOS-B) for high-resolution, inertial wave resolving measurements at 50–300 m.

Mobile

- (4+) SWIFTs measure surface waves during the process cruise.
- (20) MRV ALAMO profiling floats measure T–S from the ice–ocean interface or surface to 1200-m depth. Acoustic geolocation using SODA navigation array is not planned.
- (6) Integrated Autonomous Drifters instrumented for meteorological measurements, wave measurements, ice mass balance, and high-resolution ocean temperature profiles from the surface to 200-m depth.
- (4) Autonomous Ocean Flux Buoys augmented to quantify pycnocline diffusivity.
- (4) Ice-Tethered Profilers with Velocity provide high-resolution profiles of T, S, and **u** in the upper 250 m and 700 m.
- (6-10) Ice-capable Seagliders provide profiles of T, S, O_2, optical properties, and microstructure in the upper 1000 m. Mission lengths span to one year.

Ship-based

- LADCP and microstructure system augments Beaufort Gyre Exploration Project CTD casts in 2017 and 2018.
- 3D Sonic Anemometer quantifies wind stress during the process cruise.
- Shallow Water Integrated Mapping System (SWIMS) towed profiler and Modular Microstructure Profiler (MMP) for synoptic, 3D mapping of open water regions.

Modeling

- Internal wave modeling.

5.1 Pressure Inverted Echo Sounders

Five Rapid PIES and six Pop-up Data Shuttle Current PIES (PDS CPIES) will be deployed across two locations in the Canada Basin and Chukchi Sea (Figure 8). These instruments sit on the ocean floor, making measurements of bottom pressure and temperature every 10 min, in addition to vertical acoustic travel time. All versions of the PIES will be configured to make at least 90 and up to 354 travel time measurements per hour. PDS CPIES also make a point measurement of currents 50 m above the bottom every 10 min, and employ a data recovery system of pop-up capsules and Iridium satellite communications.

Vertical acoustic travel time is an integrated measure of the heat content of the overlying fluid, and the passage of warm and cold core eddies over the instrument result in changes in travel time of > 0.5 ms, well within a detectable range for the instruments. As such, they provide an inexpensive mechanism by which one of the advective pathways of heat into the Canada Basin, via eddies, may be monitored during the SODA experiment. Additional capabilities of these instruments will provide long-term monitoring of deep currents and bottom pressure.

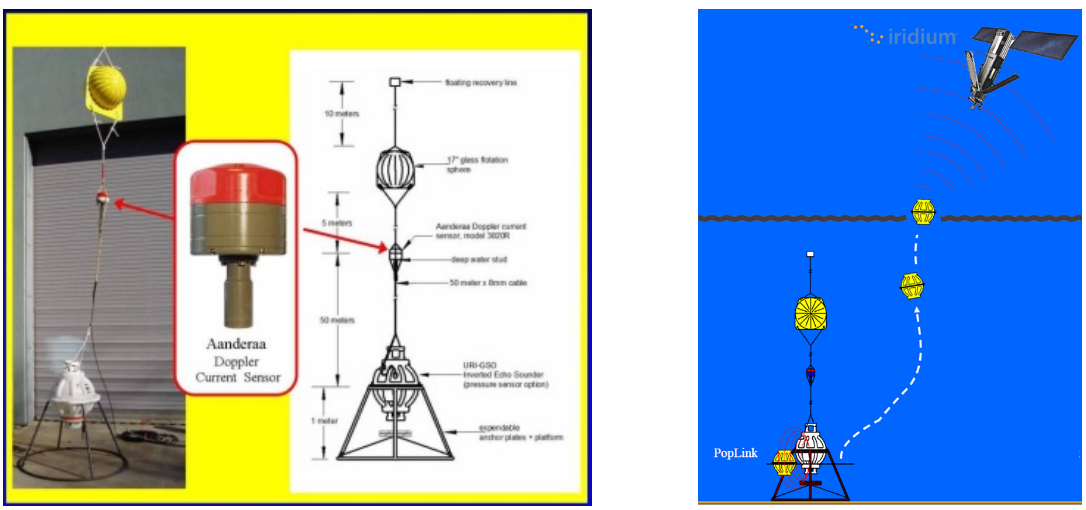

Figure 8. (Left) Photograph and schematic of a CPIES. The Pressure Inverted Echo Sounder (PIES) is mounted in a frame and held down by weights through an acoustic release. The current meter is tethered 50 m above the PIES. (Right) A schematic of the PopLink PDS system for yearly transmission of data from a CPIES via Iridium satellite.

5.2 Moorings: SODA-A, B, and C

Three heavily instrumented moorings define a fixed frame of reference and provide a high vertical resolution time series of upper ocean stratification and velocity (Figure 9). Moored instruments will sample rapidly to resolve most of the internal wave band (from near the 6-cycle hr^{-1} buoyancy frequency through the inertial), in addition to quantifying variability at longer time scales.

Central Beaufort moorings will be instrumented to provide high-resolution measurements of velocity, temperature, and salinity in the upper 200 m, with coarser measurements extending to 500 m. A 500-kHz upward looking Nortek Signature located at about 40-m depth and a 300-kHz upward looking ADCP at 80-m depth will provide rapid sampling at 2-m vertical resolution in the upper 80 m, while a downward looking 75-kHz Long-Ranger ADCP will provide 8-m vertical resolution from 80 m to 400–700 m, depending on the concentration of scatterers. A mix of Seabird MicroCATs (temperature and salinity) and less costly Seabird temperature sensors will quantify stratification below the 40-m Stablemoor depth with the same vertical resolution (2 m) as for velocity and shear, while a densely instrumented (0.5-m resolution) temperature chain will span the region from 40 m to near the sea surface, a region threatened by ice. A multibeam sonar will measure ice draft over a relatively wide swath, supplemented by Nortek Signature point measurements of ice draft and drift speed.

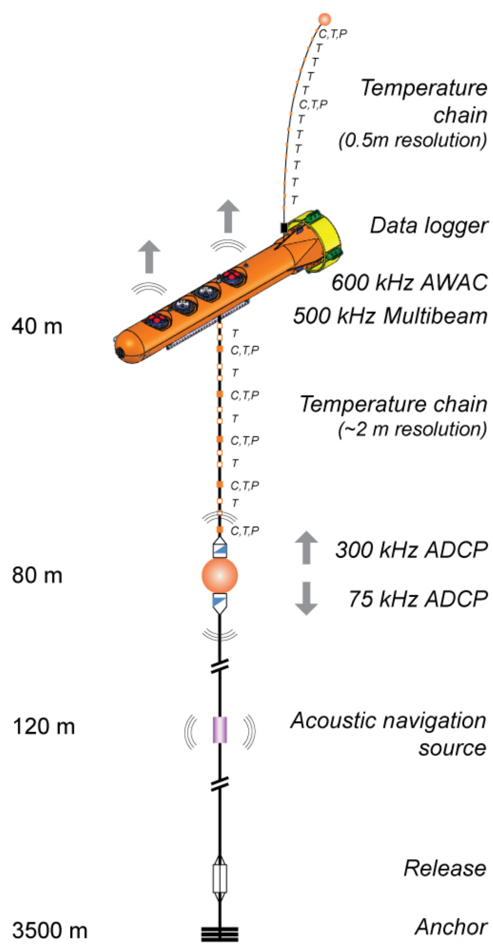

Figure 9. SODA-A, B, and C mooring configuration. The upper temperature chain is attached to the Stablemoor float by a weak link. SBE37 MicroCATs and temperature sensors will be deployed to provide coarse resolution below 80-m depth.

5.3 Acoustic Navigation Network

An array of at least seven acoustic navigation sources will be deployed to provide geolocation for Seagliders and floats. Sources will be included on moorings SODA-A, B, and C, with four additional sources deployed on independent moorings along parallel lines to the west and east. SODA will employ broadband acoustic sources based on those used in the MIZ program, but with a lower frequency, and higher power signal to provide better range. The MIZ sources achieved ranges exceeding 400 km for signals propagating within the sound channel formed by the PSW, with ranges dropping to ~100 km deeper outside the channel. The lower frequency sources designed for SODA should exceed these ranges. This source design allows encoding of information onto the navigation signal. Although the sources are capable of transmitting a small command set, this capability is of limited use in the planned configuration, without a direct communication link for passing commands to be transmitted.

5.4 Moorings: BGOS-A and BGOS-B

BGOS moorings will be augmented with an additional McLane Moored Profiler to provide profiles of temperature, salinity, and velocity at 30–300 m depth at 3-hr intervals, with a pair of profiles to 2000 m once every two days. BGOS moorings also provide measurements of ice draft from upward looking sonars and ice velocity from ADCPs.

5.5 SWIFT Floats

Surface Wave Instrument Float with Tracking (SWIFT) drifters (Figure 10) will be deployed as part of the ship-based process study. SWIFTs measure wind speed, wave height, wave directional spectra, air temperature, sea surface temperature, surface currents, and dissipation by turbulence. SWIFTs will be relocated one or more times during the course of the experiment to sample in tandem with the towed profiling surveys.

5.6 MRV ALAMO Floats

SODA will deploy next-generation ALAMO profiling floats developed by MRV Systems (LLC) (see http://www.mrvsys.com/products-and-services/mrv-alamo) fitted with conductivity-temperature-depth sensors manufactured by Sea Bird Electronics, Inc. Their relatively small size, 9 kg vs. 19 kg compared to the current generation Argo-style SOLO-2 float, make it a desirable candidate for the higher-risk arctic environment. In addition, the firmware that drives ALAMO floats has been completely rewritten to replace very old legacy code. The first of these floats have been deployed for hurricane research (see http://alamo.whoi.edu) and have demonstrated the ability to profile rapidly 12 times per day to 300 m for 100 days. For the work proposed here, a much slower profiling frequency will preserve float batteries, extending the observation period to two years. For SODA, the floats will be configured to safely sit on the bottom between profiles when deployed over the continental shelf, and to store data internally should sea ice block their ability to telemeter to satellite (sending the backlog when next able to see the sky).

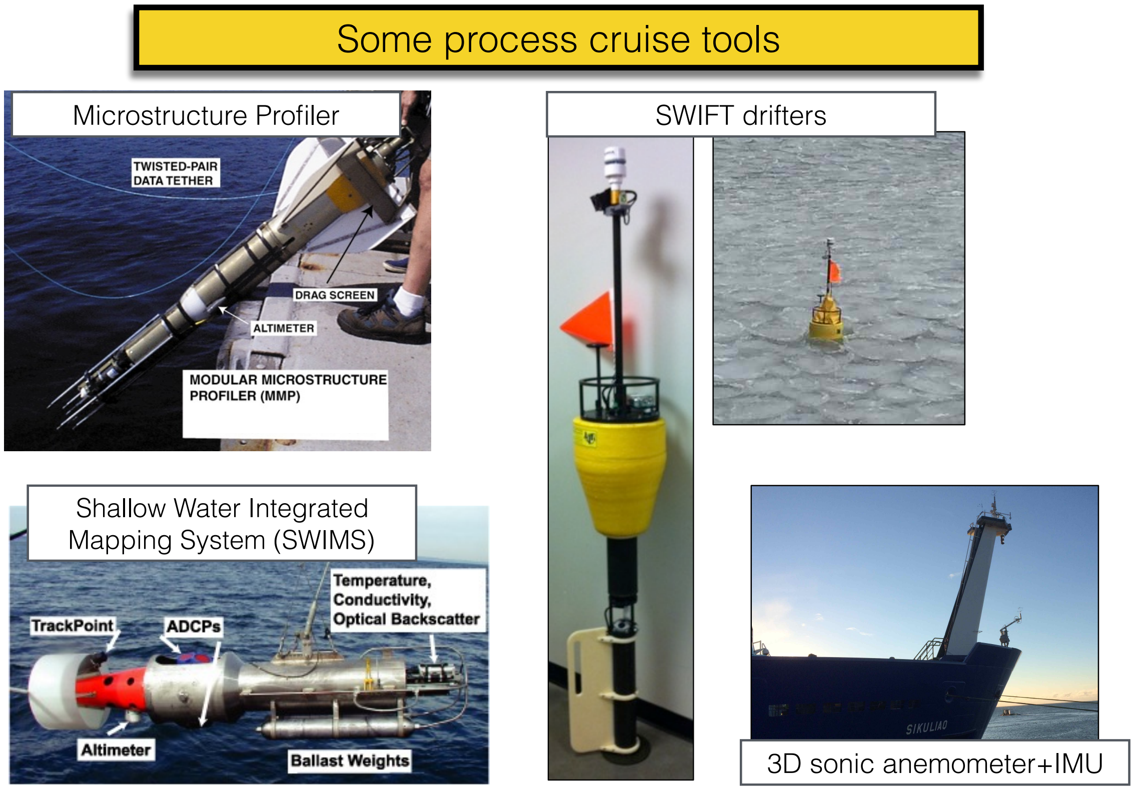

Figure 10. Proposed tools to be used during the process cruise. Clockwise from upper left: the Modular Microstructure Profiler (rapid tethered profiling down to 300 m), SWIFT drifters for short deployments from the ship (new versions have ADCPs and C-T chains), meteorological instrumentation on the mast, and the SWIMS towed body.

5.7 Integrated Autonomous Drifters

The Integrated Autonomous Drifters (IAD) extend the high-resolution temperature sensor strings of the Ice Mass Balance buoys from a length of 5 m to the upper 200 m of the water column. The long, densely-populated string measures upper ocean temperature structure at high vertical (25 cm) and temporal (2 min) resolution. Sensor spacing will be optimized with respect to anticipated upper ocean temperature structure. The planned vertical resolution for the string is 1 m above 25 m, 25 cm at 25–60 m, and 2 m below that. Beyond resolving the temporal displacement of temperature layers in the ocean by internal waves, the string may provide new insights as it drifts across mesoscale features, quantifying horizontal temperature gradients in unprecedented detail. The IADs will incorporate a ‘classic’ IMB string using 2-cm vertical resolution sensors to track snow, ice, and the immediate under-ice ocean.

IADs will also measure waves and orient themselves using an Attitude and Heading Reference System (AHRS). This updates the SBG IG-500s used in the MIZ DRI to SBG Ellipse-As, which demonstrated improved performance in the recent Sea State of the

Emerging Arctic Ocean DRI fieldwork. The surface float employs an RM Young wind speed and direction sensor, which improves year-round reliability compared to sonic anemometers that can ice in the winter. The new RM Young sensor will quantify high-frequency wind forcing, important for understanding ice–ocean coupling. Finally, the surface package will contain the usual control and communications software based on the 2014 MIZ drifters and updated to use the Iridium RUDICS protocol, as was implemented successfully for the summer 2016 Beaufort Sea wavebuoy deployments.

5.8 Autonomous Ocean Flux Buoys

Autonomous Ocean Flux Buoys (Figure 11) will quantify vertical turbulent fluxes as part of four drifting ice-based clusters. Each buoy measures thermal structure from 4-m depth up into the ice, and measures the vertical turbulent fluxes of heat, salt, and momentum using direct eddy-correlation methods near the top of the ocean mixed layer, and vertical heat fluxes within a 6-m layer in the seasonal pycnocline. These enhanced flux buoys have a surface buoy that sits on the ice, with a bulk meteorology and shortwave solar radiation sensor attached to the buoy housing 1.5 m above the ice, and precision tilt and inertial motion sensors within the buoy hull to detect both distant and near wave effects on the local ice floe.

An instrument frame hangs from the housing by a series of torsionally rigid poles to support the ocean flux package and a 16-element, mK-resolution thermistor string to measure summer heating layers immediately below the ice. The flux package instrument frame is equipped with a downward looking 300-kHz ADCP (RDI Workhorse) to measure current structure down into the pycnocline every 2 m. The surface housing also contains processing and control electronics, Global Positioning System (GPS) electronics, an Iridium satellite modem, GPS and Iridium antennae, and both primary lithium cell batteries and a solar power system. After field installation, AOFBs maintain twice-daily, two-way communications with a computer running at the Naval Postgraduate School, allowing transmission of the full data time series and routine updates of sampling parameters. The buoy system has a hull and floatation system capable of surviving multiple melt-out and freeze-up events.

5.9 Ice Tethered Profilers

Four autonomous Ice-Tethered Profilers with Velocity (ITP-Vs, Figure 12) will quantify the seasonally varying upper ocean stratification and velocity field, and the turbulent ice–ocean exchanges of heat and momentum in the Arctic MIZ. High spatial (1-m) and temporal (3-hr) resolution profile observations of upper ocean temperature, salinity, and velocity will be provided in near-real time from the ice–ocean interface to 250 m depth. This high temporal resolution will allow the characteristics and intensity of near-inertial motions and higher-frequency internal waves and their associated shears and strains to be quantified. In addition, direct estimates of the turbulent vertical fluxes of heat, salt, and momentum just below the ice–ocean interface will be made every four hours. The ITP-V array will document the changes in internal wave properties, turbulent fluxes, and entrainment of subsurface heat into the mixed layer as the sea ice concentration evolves during the melt season. The array will also provide initialization or validation data for numerical models, and will capture many of the processes important to the seasonal evolution of the sea ice cover.

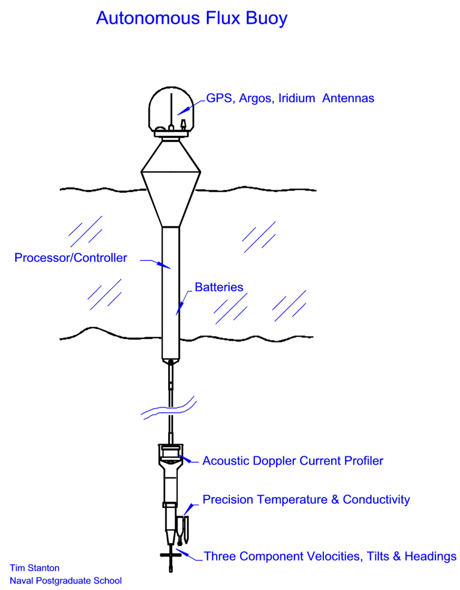

Figure 11. The Naval Postgraduate School Autonomous Ocean Flux Buoy (AOFB). A surface buoy sits on the ice supporting an instrument package suspended into the upper ocean by a series of poles from the bottom of the surface buoy. The surface buoy contains processing electronics, GPS and Iridium antennae, and batteries. The instrument package is outfitted with a downward looking 300-kHz ADCP (RDI Workhorse) and a custom-built flux package. Additionally, the buoys have GPS receivers for measuring position and calculating ice velocity. After installation in the field on selected ice floes, AOFBs maintain twice-daily, two-way communications with a computer running at the Naval Postgraduate School.

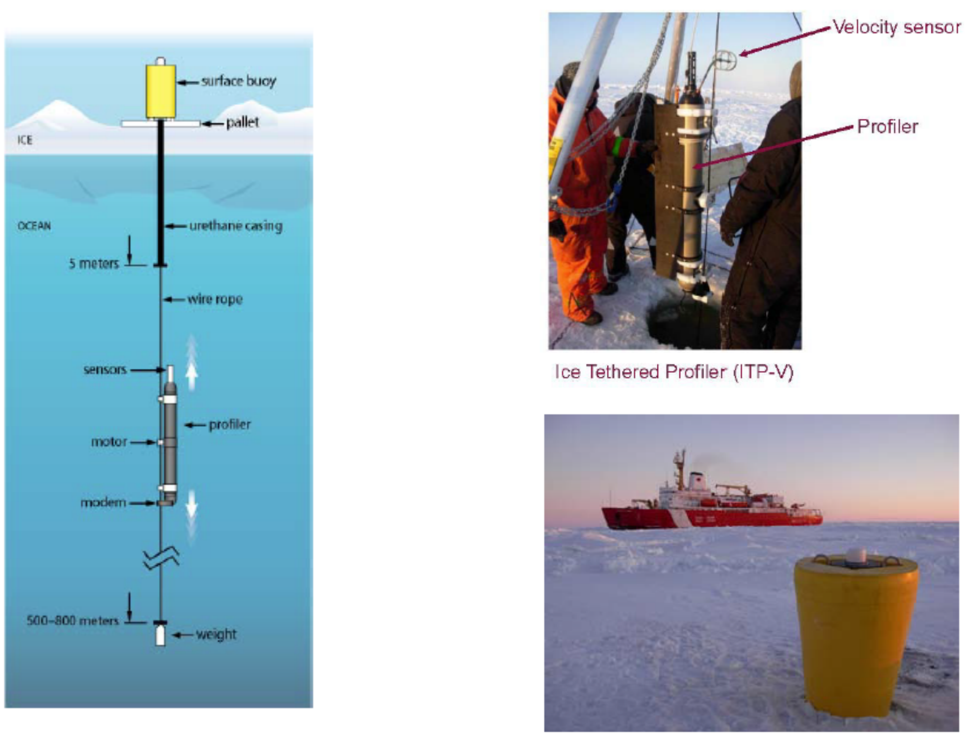

Figure 12. Schematic of the Woods Hole Oceanographic Institution Ice-Tethered Profiler system (left), the pre-deployment profiler with velocity sensor (ITP-V; upper right), and the surface expression (lower right).

5.10 Ice-Capable Seagliders

Long-endurance, autonomous Seagliders (Figure 13) have been used in extended missions in ice-covered waters (e.g., MIZ DRI). They will occupy repeat sections around the Central Beaufort mooring array, sampling through a complete annual cycle, complementing the highly-resolved mooring time series to provide four-dimensional sampling of the upper ocean. Gliders will occupy long sections that span the length of the mooring array, small survey patterns meant to resolve the mesoscale and submesoscale around SODA-B, and short lines that follow the ice edge during melt-out and freeze-up. At a typical speed of 0.25 m s^{-1} (23 km day^{-1}) a single glider would require roughly one month to transit from 73.5°N to 78.5°N, the longest of the planned sections. Repeat time could be halved by sampling with two vehicles.

A combination of recent advances in Seaglider technology and an operating schedule that may include periods of hibernation and drift between sections will provide full-year endurance. When operating in ice-covered waters, gliders navigate by trilateration from moored acoustic sound sources (or dead reckoning should navigation signals be unavailable) and incorporate enhanced autonomy to perform functions such as sensing overhead ice, determining when to attempt to surface, and decision making in the event of lost navigation or instrument malfunction. Hibernating gliders will continue to track their position, waking to reposition should they drift too far from their target region. Gliders will measure temperature, salinity, dissolved oxygen, rates of dissipation of temperature variance (and vertical turbulent diffusivity), and multi-spectral downwelling irradiance.

Figure 13. APL-UW ice-capable Seagliders. Gliders are small (50 kg, 1.5 m), long-endurance (multi-month), buoyancy-driven vehicles capable of navigating survey patterns while diving from the surface or ice–ocean interface to depths up to 1000 m. Iridium satellite modems provide two-way communications for command and data upload. Payload includes Seabird T and C, dissolved oxygen, downwelling irradiance, and temperature microstructure.

5.11 LADCP and Microstructure Measurements

The Beaufort Gyre Observing System (BGOS) program surveys the Beaufort Sea each August/September taking full-depth CTD rosette casts at approximately 40 stations. The program yields broad coverage of the Beaufort Gyre, including some stations near the shelf (Figure 14). The BGOS shipboard sampling program will be augmented by adding lowered ADCP (LADCP) and turbulence sensors (micro-temperature and shear) to the CTD rosette. These observations will provide basin-scale coverage of turbulence and internal wave shear in the upper ocean. Full depth casts will be taken, but small turbulence levels and backscatter levels will likely preclude meaningful signals at depth.

The LADCP system will be enhanced for operation at high latitudes by configuring an inertial measurement unit (IMU) to operate with the LADCP so that heading in particular can be determined accurately. Microstructure observations will consist of micro-temperature and micro-shear sensors attached to the CTD. It is anticipated that the micro-shear observations will have a much smaller useful depth range than micro-temperature observations, perhaps limited to 20–30 m below the mixed layer base. (If micro-shear observations are not sufficiently sensitive to observe signals over even this limited depth range, then micro-conductivity sensors will be used instead.)

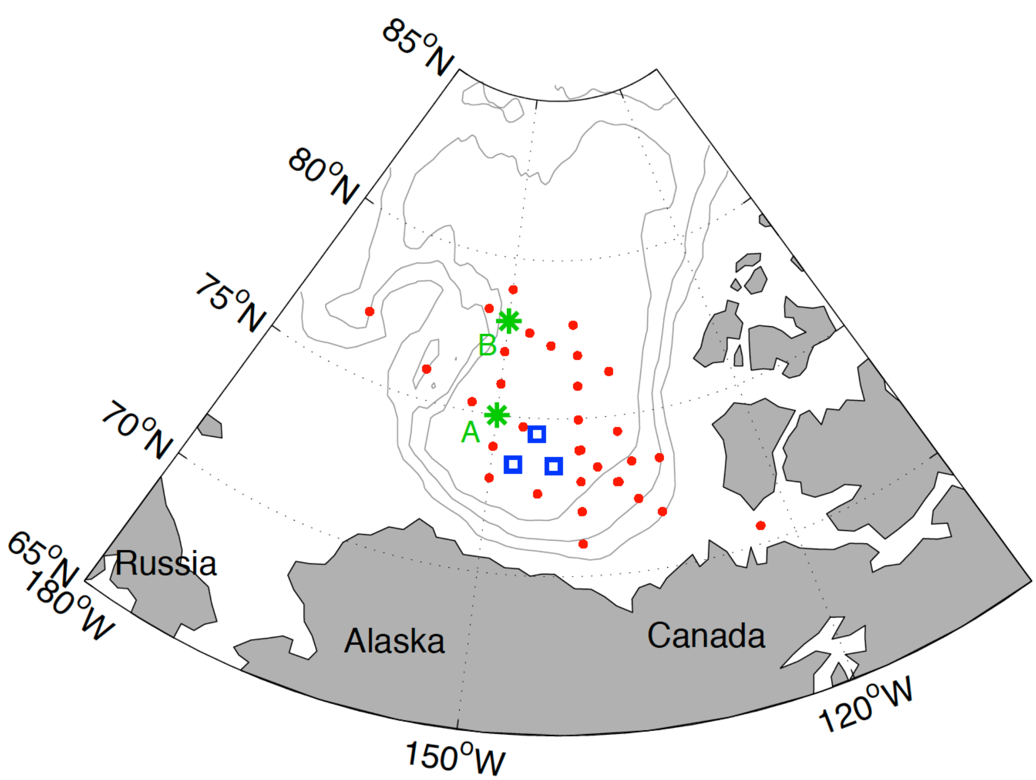

Figure 14. Chart of the Canada Basin. Green asterisks mark the locations of BGOS-A and B moorings, with red dots marking BGOS CTD stations.

5.12 3D Sonic Anemometer

A 3D sonic anemometer mounted on the bow of the ship (Figure 10) during the process cruise will provide direction measurements of wind stress using inertial dissipation and covariance methods. The results will be used to quantify the momentum flux from the atmosphere to the ocean, and to map variations in the air–ice–ocean drag coefficients. A similar measurement will be made using a new generation (v4) of SWIFT drifters, recently funded via a DURIP award.

5.13 Shallow Water Integrated Mapping System and Modular Microstructure Profiler

These two ship-based tools are designed to be used in complementary mode to map upper ocean temperature, salinity, and structure and associated turbulence. Both were developed by Mike Gregg at APL-UW and now renovated and operated by Matthew Alford (now at Scripps Institution of Oceanography) and colleagues (Figure 10).

The MMP is a loosely tethered microstructure profiler that carries a pumped CTD, shear probes, and FP07 thermistors for velocity and temperature microstructure with a noise floor near 10^{-10} W kg^{-1}. Shear-based microstructure provides a ground truth to temperature-based microstructure methods. MMP is deployed from the stern of the ship with a twisted-pair cable. Profiles to 300 m can be done every 15–20 min.

SWIMS is towed behind a ship and winched up and down from the surface giving tight saw-tooths to about 500–600 m maximum depth depending on tow speed up to 6 kn. It carries upward and downward looking ADCPs, two pumped CTDs, optical backscatter, and a temperature microstructure package (χ-ometer).

6. Data Dissemination

The SODA program will employ a lightweight data distribution structure consisting of a password protected, central repository for storing and distributing project data and model output, along with associated documentation. To promote broad use of the data, and to encourage active collaboration, open access, governed by the SODA program data policy (Section 7), will be provided to all SODA investigators.

To facilitate use in numerical efforts, to provide guidance for ship-based efforts, float deployments, and mobile platforms, and to assist collaborating programs, data will be posted as rapidly as possible. Specific data and product needs for SODA numerical efforts include:

Atmosphere

Validation of atmospheric forcing used in ice–ocean models, air drag as a function of ice floe size, experimental and statistical relationship between air drag and floe size

Prediction of SAT, winds, shortwave and long-wave downward radiation, surface heat flux, clouds/moisture/aerosol

Sea ice

Thickness distribution, concentration, extent, drift, deformation, temperature and salinity profiles, regional ice floe size distribution, ridges and ridging, stress, melt ponds, albedo, radiative fluxes, ice–wave interactions

Ocean

SST and SSS, mixed layer depth, seasonal pycnocline, upper halocline depth, waves, upper ocean (0–150 m), 3D currents in different seasons, ice–ocean momentum and heat fluxes, heat entrainment into the mixed layer, mixing and diffusion (turbulence and double diffusion), upper ocean heat and freshwater content

Each observational component will plan for a hierarchy of data release that should include:

1. Quick-release products that incorporate minimal quality control and processing.
2. Delayed-mode products, delivered in time for use in the analysis phase, that incorporate full quality control, processing, and correction. These products will be versioned to accommodate updates as additional issues are identified and corrected.

Delayed-mode data should be accompanied by full documentation describing platform, instrument, sensors (including precision and accuracy), quality control, calibration, and correction procedures.

A Data Coordination Working Group will be formed from the SODA PIs. This team will be responsible for working with the various program components to establish mutually agreed upon data formats and to coordinate delivery, distribution, and archiving of observational data and model output.

7. Data Policy

The ONR Stratified Ocean Dynamics of the Arctic (SODA) program consists of all investigators participating in the integrated efforts associated with the SODA Departmental Research Initiative (DRI). This includes the core team of ONR-supported investigators funded directly by the SODA DRI and investigators funded though other mechanisms, but coordinated as part of the SODA program. SODA DRI data will include observations from field programs, remote sensing data, and model results, all of which will be treated equally for the purposes of the program data policy. All data are collected for basic research, and will be unclassified. As the SODA DRI also represents an ONR contribution to the U.S. interagency Study of Environmental Arctic Change (SEARCH) and the U.S. interagency Arctic Observing Network (AON), data will also be released to the official data management facility of the U.S. AON for archiving, dissemination, and curation.

Given the complex nature of the science questions and challenges associated with collecting the necessary observations, the success of the SODA program depends on open, effective data sharing and collaboration. To facilitate sharing of data and collaboration between SODA scientists, the SODA DRI will establish a program data archive. To further promote and support sharing and collaboration, the SODA DRI specifies policies to govern the use of data collected under the program.

Data use

It is not ethical to publish data without proper attribution or co-authorship. The data are the intellectual property of the collecting investigator(s).

The intellectual investment and time committed to the collection of a data set entitles the investigator to the fundamental benefits of the data set. Publication of descriptive or interpretive results derived immediately and directly from the data is the privilege and responsibility of the investigators who collect the data.

There are two possible actions for any person making substantial use of SODA data sets, both of which require discussion with and permission from the data collector:

1. *Expectation of co-authorship*
   This is the usual condition. Scientists making use of the data should anticipate that the data collectors would be active participants and require co-authorship of published results.
2. *Citation and acknowledgment*
   In cases where the data collector acknowledges the importance of the application but expects to make no time investment or intellectual contribution to the published work, the data collector may agree to provide the data to another scientist provided data reports are properly cited and the contribution is recognized in the text and acknowledgments.

Authors must share and discuss manuscripts with all SODA investigators who contributed data prior to submission anywhere.

Agreements about publication, authorship, or citation should be documented at a minimum by email between the investigators.

Roles and Responsibilities

Principal investigators who are responsible for the collection of observational data or generation of model data during the SODA DRI are considered participating SODA DRI scientists and may request data from and provide data to other participating scientists.

Participating scientists have primary responsibility to quality control their own data and make it available to the rest of the SODA participating scientists on a timely basis.

Data should be released as soon as possible, through the SODA data archive, along with documentation that can be used by other researchers to judge data quality and potential usefulness.

The data contained in the archive are made available even though they may not be “final” (i.e., error free) data so it is the responsibility of the user to verify the status of the data and to be aware of its potential limitations.

Participating scientists who wish to use others’ data sets are responsible for notifying those principal investigators of their intent and inviting collaboration and/or co-authorship of published results.

Participating scientists must consider the interests of graduate students and postdocs before publishing data. Plans for graduate student and postdoc projects must be discussed openly and effort made by all SODA DRI investigators to facilitate and protect these efforts.

For the duration of the SODA DRI (2016–2020), program data will be restricted to SODA DRI investigators. Dissemination beyond program investigators will require the agreement of SODA DRI investigators and the cognizant ONR program managers. After this time, SODA DRI participating investigators are required to submit their data to the official data management facility of the U.S. AON for public dissemination and long-term curation.

The SODA DRI prohibits third party data dissemination; participants are not allowed to redistribute data taken by other SODA investigators.

All potential users who access the data will be reminded of the SODA DRI commitment to the principle that data are the intellectual property of the collecting scientists.

Program sponsors of participating scientists may arbitrate and reach agreement on data sharing questions when they arise.

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14. ABSTRACT

Vertical and lateral water properties and density structure within the Arctic Ocean are intimately related to the ocean circulation, and have profound consequences for sea ice growth and retreat as well as for propagation of acoustic energy at all scales. Our current understanding of the dynamics governing arctic upper ocean stratification and circulation derives largely from a period when extensive ice cover modulated the oceanic response to atmospheric forcing. Recently, however, there has been significant arctic warming, accompanied by changes in the extent, thickness distribution, and properties of the arctic sea ice cover. The need to understand these changes and their impact on arctic stratification and circulation, sea ice evolution, and the acoustic environment motivate the Office of Naval Research (ONR) Stratified Ocean Dynamics of the Arctic Departmental Research Initiative.

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